Exxon Valdez Oil Spill
Long-Term Monitoring Program (Gulf Watch Alaska) Final Report

Monitoring Long-Term Changes in Forage Fish Distribution, Abundance and Body Condition

Exxon Valdez Oil Spill Trustee Council Project 16120114-O
Final Report

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Study History: This 5-year project was funded as part of the Gulf Watch Alaska long-term monitoring program by the *Exxon Valdez* Oil Spill Trustee Council. Previous work on forage fish in Prince William Sound included aerial and hydroacoustic surveys conducted during the Alaska Predator Ecosystem Experiment and Sound Ecosystem Assessment. This study differed from other monitoring projects within Gulf Watch Alaska because the primary objective was to determine robust methods to monitor forage fish in the spill-affected region. Original protocols involved a sound-wide systematic sampling design; however, after consulting with science and program managers, in 2014-2016 we modified the study design to include a random stratified aerial-acoustic survey design. This final report builds off of the Gulf Watch Alaska science synthesis work (Appendix A).

Abstract: We collected data on forage fish abundance, distribution and body condition in Prince William Sound, Alaska during summers in 2012 through 2016. This included acoustic – trawl surveys, aerial-acoustic surveys, opportunistic sampling where we encountered forage aggregations, and concurrent measurements of forage fish habitat. Acoustic indices of density suggest low abundance of age-0 walleye pollock (*Gadus chalcogrammus*), capelin (*Mallotus villosus*), and krill (Euphausiacea), but higher abundance of age-0 (< 80 mm), age-1 (80-140 mm) herring, and gelatinous zooplankton in 2015. Aerial school density of adult herring was highest in 2015 compared to 2014 or 2016, but acoustic indices of adult Pacific herring (*Clupea pallasii*) did not follow the same pattern. Weight-length-age relationships differed significantly among years for capelin and Pacific sand lance (*Ammodytes personatus*), with higher body condition in 2013 and 2012 than in 2014 and 2015. This work has provided information on prey resources in coastal areas of the Gulf of Alaska that is consistent with recent observations in the larger Gulf of Alaska region. Ongoing analyses will be important in understanding the marine ecosystem response to anomalously warm conditions beginning in 2014.

Key words: acoustic-trawl, aerial survey, capelin (*Mallotus villosus*), forage fish, krill (Euphausiacea), Pacific herring (*Clupea pallasii*), Pacific sand lance (*Ammodytes personatus*), Prince William Sound, walleye pollock (*Gadus chalcogrammus*)

Project Data: All datasets are available in comma delimited format with a unique station ID number, data includes:

- Echointegration data from the aerial-acoustic random stratified forage fish surveys. Acoustic data were obtained from a hull-mounted SIMRAD ER60 split beam dual frequency echosounder operating at 120 and 38 kHz. Both transducers were calibrated at the start of each survey.
- Fish catch and morphological data from various net sampling methods including modified herring trawl, beach seine, cast net, dip net, jig, gill net and purse seine.
- At-sea distribution and abundance of marine birds and mammals. Transects were conducted following standard U.S. Fish and Wildlife protocols for strip transect surveys and modified for work in coastal Alaska.
- Zooplankton biomass. Samples were collected with a 150 micron mesh 0.25 m diameter paired ring net on a 50 m vertical haul during daylight hours.

- Conductivity – temperature – depth (CTD) profiles. Oceanographic conditions were sampled with a Seabird Electronics SBE19 (2012) and SBE19Plus v2 (2013-2015) CTD equipped with various sensors (e.g., oxygen, pH, fluorescence, turbidity, beam transmission and photosynthetically active irradiance).
- Inorganic nutrient concentration, including phosphate, nitrate, nitrite and silicic acid.

These data are archived by the Gulf Watch Alaska's *Exxon Valdez* Oil Spill Trustee Council and U.S. Geological Survey. There are no limitations on the use of the data, however, it is requested that the authors be cited for any subsequent publications that reference this dataset. It is strongly recommended that careful attention be paid to the contents of the metadata file associated with these data to evaluate data set limitations or intended use.

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Citation:

Arimitsu, M. L., J. F. Piatt, B. Heflin, V. von Biela, S. K. Schoen. 2018. Monitoring long-term changes in forage fish distribution, abundance and body condition. *Exxon Valdez* Oil Spill Long-term Monitoring Program (Gulf Watch Alaska) Final Report (*Exxon Valdez* Oil Spill Trustee Council Project 16120114-O). *Exxon Valdez* Oil Spill Trustee Council, Anchorage, Alaska.

CONTENTS

LIST OF TABLES

LIST OF FIGURES

EXECUTIVE SUMMARY

Sampling of forage fish in Prince William Sound has been in progress for decades, but the long term monitoring of these non-fished species for assessment of distribution and abundance has seldom been done in a practical manner across time and species. Forage fish are difficult to study because there are several species, with diverse life histories and different use of habitats. Our first goal was to identify practical survey methods that could be maintained over the long term for several species.

We tested a variety of methods to monitor forage fish in Prince William Sound. Our original approach included a stratified systematic sampling design but was discontinued because the effort was concentrated in poor forage fish habitat where frequency of occurrence of target species was too low to adequately describe distribution or abundance at the sound-wide scale. Beginning in 2014, we tested an approach that combined aerial surveys and acoustic-trawl surveys, using existing aerial shoreline data on school distribution and persistence to identify density strata within the study region. We found this method was more useful than the systematic design because it targeted more suitable habitat for the most common species of forage fish. Although we would recommend the aerial-acoustic methods as a means to monitor forage fish populations in Prince William Sound into the future, the Gulf Watch Alaska principal investigators collectively agreed that a more cost effective and practical approach would include greater integration within the pelagic ecosystem component. We identified the need for tighter coupling of the predator and forage fish (i.e., prey) monitoring. Additionally, there was consensus by the entire Gulf Watch Alaska program that support for the long-term dataset on seabird diets at Middleton Island was a priority. Thus, the Gulf Watch Alaska forage fish project will continue with a revised focus in 2017 – 21.

We collected data on forage fish abundance, distribution and body condition in Prince William Sound, Alaska in summers in 2012 through 2016. This included acoustic–trawl surveys, aerial-acoustic surveys and opportunistic sampling where we encountered forage aggregations. We also sampled forage fish habitat, biological, and oceanographic conditions during surveys in each year.

Weight-length relationships differed significantly among years for age-1 capelin (*Mallotus villosus*), with highest body condition in 2013, and decreasing weight at length in 2012, 2014 and 2015. In 2015 age-1 capelin were longer but weighed less than other years. Age-1 capelin were missing from the population in 2016, despite sampling in deep water and thermal refuges where they typically occur.

Young of the year walleye pollock (*Gadus chalcogrammus*) were most abundant in 2012 and least abundant in 2015. Observations in Prince William Sound were consistent with what is known from the Gulf of Alaska walleye pollock stock assessment conducted by the National Oceanic and Atmospheric Administration.

This work has provided information on prey resources in coastal areas of the Gulf of Alaska that will be used to understand the marine ecosystem response to anomalously warm conditions beginning in 2014. For example, the information on recent changes in body condition of capelin and sand lance (*Ammodytes personatus*) is of high value to Department of the Interior managers who are investigating the cause of the widespread and unprecedented murre die off in the Gulf of Alaska during the winter of 2015-16. Additionally, the capelin age-length and distribution data collected during this project will be used in the Gulf of Alaska Integrated Ecosystem Research Program synthesis effort to document the life history of capelin in the northern Gulf of Alaska. Working with the National Marine Fisheries Service stock assessment team, we have also identified forage fish size and growth metrics that may be used to inform fisheries managers as part of their ecosystems-based fisheries management efforts in the future.

INTRODUCTION

Fluctuations in forage fish abundance can have dramatic ecosystem effects because much of the energy transferred from lower to higher trophic levels passes through a small number of key forage species (Cury 2000). Forage fish typically produce a large number of offspring and have short lifespans, and these traits predispose populations towards large fluctuations in abundance, with associated impacts on predators. In response to a lack of recovery of wildlife populations following the *Exxon Valdez* oil spill (EVOS), and evidence of natural background changes in forage fish abundance, there was a significant effort to document forage fish distribution, abundance, and variability in Prince William Sound (PWS) in the 1990s. Since then, ongoing research has focused on commercially valuable Pacific herring *(Clupea pallasii)*, whereas less has been done to monitor other ecologically important forage species such as Pacific sand lance (*Ammodytes personatus)*, capelin (*Mallotus villosus*), eulachon (*Thaleichthys pacificus)* and euphausiids (Euphausiacea), all included hereafter under the label of "forage fish".

Forage species are difficult and expensive to monitor because they are patchy in their distribution and are comprised of species with different life histories and habitats. Many investigators have attempted to document forage fish distribution, abundance, and variability in PWS and Cook Inlet since the 1990s (Norcross et al. 1999, Stokesbury et al. 2000, Thedinga et al. 2000, Brown 2002, Ainley et al. 2003, Abookire and Piatt 2005, Speckman et al. 2005, Piatt et al. 2007); but for PWS, none have provided population estimates that can be tracked annually in a cost-effective and practical manner. Survey methods for estimating abundance and distribution of forage fish included acoustic surveys coupled with trawl-sampling (Haldorson et al. 1998, Stokesbury et al. 2000, Thedinga et al. 2000, Speckman et al. 2005) and Sound-wide aerial surveys for surface-schooling fish (Brown and Moreland 2000).

Net sampling is useful for providing catch per unit effort (CPUE) indices to assess relative abundance, age structure, and body condition relative to environmental conditions (Robards et al. 2002, Piatt 2002). Catch-at-age data is useful for estimating abundance and other population parameters (Quinn II and Deriso 1999). Age assessments are essential for understanding population dynamics by monitoring year-class strength over time. It is also useful to understand whether mean size at age (growth) changes relative to changing environmental conditions (von Biela et al. 2011) and whether those changes are consistent across species (Wagner et al. 2007). Few studies have examined age structure of forage species in Alaska. However, otoliths can be used to age capelin and Pacific sand lance (Pahlke 1985, Robards et al. 2002).

The lack of time series data on abundance and distribution of these forage species in PWS, and the spatial and temporal variability inherent to these populations makes it difficult to assess population status and trends of most forage species. Beginning in summer 2012, we implemented a program to identify robust methods to monitor forage fish in PWS. In this report we provide information on the distribution, abundance, body condition and habitat of forage fish in PWS, as well as guidance on practical cost effective procedures for monitoring forage fish populations in PWS.

OBJECTIVES

1) Identify robust indices for monitoring forage fish populations over time and devise a sampling strategy for long-term measurement of those indices,
2) Assess the current distribution, abundance, species composition, and body condition of forage fishes (other than herring) in selected areas of PWS at selected times of the year, and
3) Relate abundance and distribution of forage species to abiotic characteristics of the marine environment.

METHODS

Study Area

PWS is a complex fjord-estuary located in south-central Alaska. This region covers about 8,800 km^2 with over 3,200 km of shoreline. The study area contains a diversity of marine habitats marked by shallow basins, narrow passages, deep fjords, and large embayments. The Chugach Mountains form the border along the mainland and large glacial ice-fields end in tidewater glaciers near the head of some fjords. Conceptual models suggest that natural processes, such as climate change and physical/chemical oceanographic processes, play a dominant role in shaping the marine ecosystem in PWS and the Gulf of Alaska (Peterson et al. 2003, Harwell et al. 2010). The pelagic system in which forage fish play a key role is structured mainly by variability in ocean climate-related stressors such as salinity, temperature, nutrients and suspended sediments (Harwell et al. 2010, Arimitsu et al. 2016).

Data Collection and Analysis

Objective 1: Forage Fish Survey Methods

Survey Design

To meet objective 1, based on our previous experience in PWS and other coastal systems, the advice of fisheries scientists and statisticians, as well as agency and academic researchers who had previously worked on *Exxon Valdez* Oil Spill Trustee Council (EVOSTC)-funded projects (e.g., Alaska Predator Ecosystem Experiment [APEX] and Sound Ecosystem Assessment [SEA]), we evaluated systematic and random stratified survey designs to quantify the distribution and abundance of forage fish in the sound.

Initially we developed a systematic survey design which was based on theoretical concepts of acoustic-trawl monitoring for fisheries research (Simmonds and MacLennan 2005) and practical guidance for operating procedures of acoustic surveys (Parker-Stetter et al. 2009). Stations were chosen by overlaying a grid of 306 km^2 in length cell size over navigable waters in PWS. The grid cell size was determined by the number of stations we expected to be able to sample (i.e., 22 stations in the core area to be sampled each year, and 9 stations in the north or east area to be sampled in alternating years) given the resources available. At each station, a set of acoustic transects equal to 25 km (~ 2.25 hours per station) in length was drawn perpendicular to the depth gradient. We evaluated this design in 2012-13 (see Appendix A); however, we initially observed relatively few aggregations of small-schooling fish in areas far enough away from shore and deep enough to conduct acoustic surveys from a research vessel. By 2013 we began to develop a strategy that incorporated data from nearshore aerial forage fish surveys (E. Brown, unpublished, see Appendix A) to guide the boat-based acoustic transects and net-sampling techniques to increase our sampling efficiency.

Based on this pilot work, in conjunction with the Herring Research and Monitoring Program we conducted an aerial-acoustic survey for forage fish in 2014-2016. Historical aerial survey methods were established during the APEX and SEA projects in the late 1990s (Brown and Borstad 1998, Brown and Moreland 2000) and served as the statistical basis for a new survey design. Shoreline surveys from July 2010 – 2012 (E. Brown, Flying Fish Ltd., unpublished data) were compiled and analyzed to identify low, medium and high density regions. A 5-minute latitude by 5-minute longitude grid (to facilitate navigation in future efforts) was overlaid on previous aerial track lines and observations. Grid cells encompass 43 km^2 and varied in the amount of water and land in each. An index of school density was calculated for each grid cell such that the total number of schools observed was standardized by the amount of effort and weighted by persistence (number of years schools occurred in each cell). Grid cells from high, medium and low density strata were randomly selected for sampling of aerial school counts. The sample size in each stratum was chosen to minimize variance of the population mean.

Aerial-acoustic surveys for forage fish were conducted in July of each year. Aerial surveys provided an index of nearshore and near-surface forage fish school density. The number of schools in each sampling block was censused by an experienced spotting pilot, the primary observer, and a secondary observer, and a third individual recorded observations. Acoustic-trawl surveys were conducted to assess the vertical distribution of biomass by species in a random subset (n = 16) of navigable blocks in the high-density stratum. We conducted acoustic transects in blocks usually within 24 hours of an aerial survey in the same location.

Objective 2: Abundance, Distribution, and Body Condition of Forage Fish

Aerial Surveys

To meet objective 2, we conducted coupled aerial and acoustic surveys in July 2014-2016 (Fig. 1) using the survey design described above. In each aerial survey block, forage fish schools were counted, identified to species by an experienced commercial spotter pilot by their shape, color, and location, and classified by size using a sighting tube (Brown and Moreland 2000).

Aerial observations of species and size class were validated by a ground crew for approximately 1-2 hours each day when schools were present in the vicinity of an accompanying research vessel. In most cases, a skiff was deployed to allow greater access to shallow nearshore areas and occasionally schools were in water deep enough for the larger vessel to access. During validation efforts the aerial observers circled overhead and communicated via radio to guide the skiff or larger vessel to the school, and the ground crew deployed jigs with varying hook sizes, dip nets, cast nets, a purse seine or a submersible video camera to capture fish or images for species and size information. Validation of herring age estimates was based on the length of fish captured. In July age-0 herring are <80 mm, age-1 herring are >80 and <140 mm, and age-2+ are expected to be >140 mm (S. Pegau, Prince William Sound Science Center, unpublished data).

Aerial school density D in each block was calculated by dividing the number of schools observed by the area of water in each survey block. Stratum specific areas were determined in GIS as the following: high density = 1897 km^2, medium density = 1863 km^2, and low density = 2446 km^2. We estimated an aerial school abundance index using the following equation: $\hat{S} = \sum_v A_v \overline{D_v}$, where $\hat{S}$ is the estimated abundance of schools, V is the stratum from v = 1, …, V, A_v is the area of water in stratum v, and $\overline{D_v}$ is the mean school density in stratum v. Confidence intervals (± 95%) were calculated using bias-corrected and accelerated bootstrap (BC_a) confidence intervals. For species-specific aerial school abundance indices (sand lance and herring only) we applied a correction factor based on the school identification validation results. In each aerial survey block herring and sand lance schools were multiplied by the proportion of schools correctly identified (0.84 and 0.88, respectively). Adult herring schools were always identified correctly during validation efforts, and we assumed other herring schools were juvenile herring. Thus an index of juvenile herring was attained by the following: 0.84 x (all herring schools – adult herring schools). For sand lance, adult herring, and juvenile herring school indices, stratification and confidence intervals were calculated similar to $\hat{S}$ above. Capelin and eulachon were not encountered frequently during aerial survey and validation efforts, thus species-specific indices were not possible.

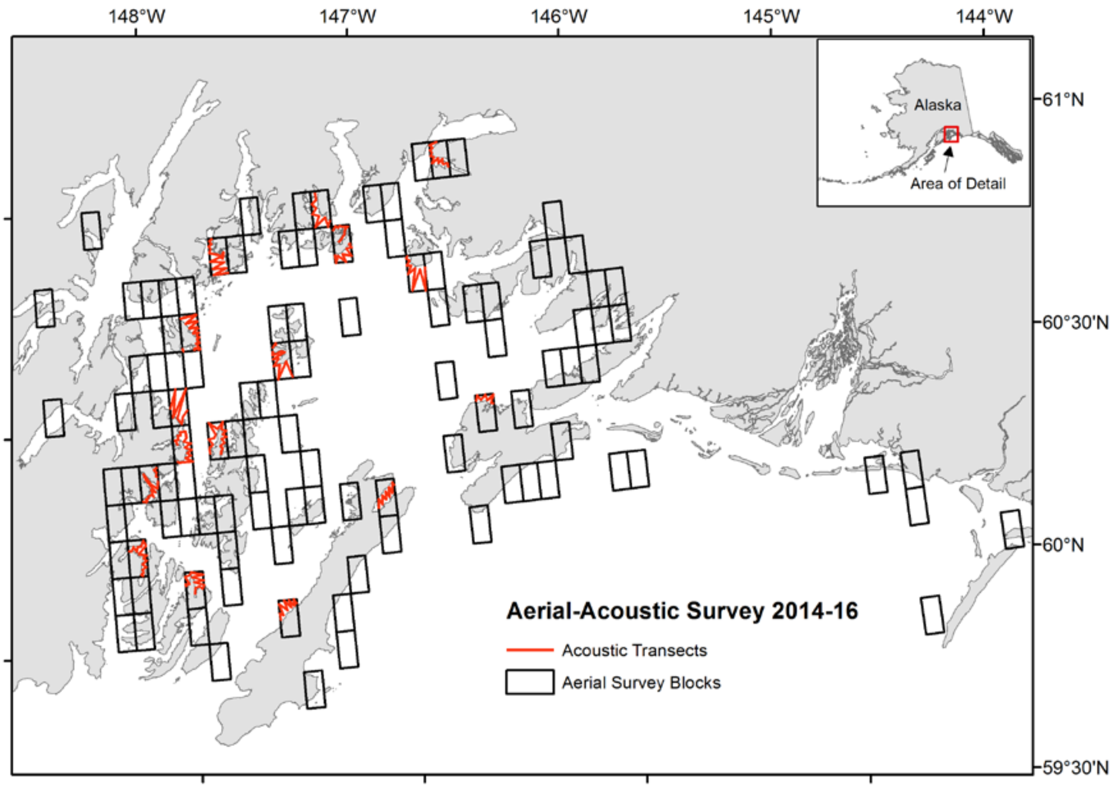

Figure 1. Aerial (blocks) and acoustic (lines) surveys for forage fish conducted in Prince William Sound, Alaska in July 2014-2016.

In each acoustic survey block (n = 16), acoustic transects were conducted from the 15 m U.S. Geological Survey (USGS) R/V *Alaskan Gyre* with a SIMRAD ER60 split beam echosounder system and hull mounted transducers operating at 120 and 38 kHz (7° and 12° beam width, respectively). Transducers were mounted 1 m below the water surface. Fixed zig-zag transects covered the navigable waters within each randomly selected high density block, and the vessel speed was held at 11-14 km h^{-1}. Data were collected with a pulse duration of 0.512 ms at a rate of 1 ping s^{-1}. Calibration of the hydroacoustic system was performed at the beginning of each survey by suspending a 38.1 mm tungsten carbide sphere of known target strength below the transducers (Table 1, Foote et al. 1987).

Fish Collections

We used a modified-herring trawl to ground-truth acoustic backscatter (i.e., to confirm species and length frequency of ensonified targets), to collect samples for measures of body condition and age structure, and to detect changes in overall community structure relative to habitat. The net is 37.2 m^2 in area at the mouth, and 62 m in length. Mesh size diminishes from 5 cm at the mouth to 6 mm in the cod end, and the net has a 3 mm cod end liner. Maximum fishing depth was 125 m. Real-time trawl depth was managed with a Notus Trawlmaster® depth sensor attached to the headrope. Flow through the net, which was used to estimate distance towed, was recorded with a General Oceanic® flowmeter. Vessel speed over ground was generally less than 3 kt (5.6 km hr^{-1}), although speed varied depending on target depth and sea conditions. We deployed the trawl net when we encountered significant acoustic sign on surveys, and occasionally, opportunistically to target species when we encountered them off survey effort to provide samples needed for age and body condition analyses.

We also used a beach seine and purse seine to target Pacific sand lance, which occur very close to shore in shallow water in coastal Alaska during the summer months (Robards et al. 2002, Ostrand et al. 2005).

The beach seine was 37 m long with diminishing mesh size from 28 mm at the wings to 5 mm at the center, and was set parallel to shore from a skiff and retrieved from the beach by 3-4 people. The purse seine was 47 m long and 6.7 m deep with diminishing mesh size from 28 mm to 3 mm at the center. Both types of seine were deployed from a skiff by 3-4 people.

During validation of aerial and acoustic surveys we also used herring jigs (hook size 4, 6, 8 and 10), cast nets (mesh size ¼" and ¾"), long-handled dip nets (mesh size 5 mm) and gill nets (60' x 16' with variable mesh panels ¼", 5/16" and 3/8" square mesh) to collect forage fish. Although not directly comparable, the use of many fishing methods was necessary to sample fish in a variety of habitats.

Fish total length was measured to the nearest mm in the field. In 2012 and 2013, target species were frozen and weighed later in the lab to the nearest 0.01 g on a laboratory scale. In 2014 – 2016, we used a Marel M2200® marine lab scale, and measurements were made to the nearest 0.05 g at sea. For all taxa, larger trawl catches were subsampled by volume. For macrozooplankton aggregations collected by trawl we also preserved 50 – 100 ml samples in 5-10% formaldehyde. In the lab 2014-15 macrozooplankton samples were identified, enumerated, and 5-10 organisms from each species weighed to the nearest 0.01 mg. In 2016, a preservation issue hampered quantification of species-specific biomass; however, presence (but not absence) of euphausiid species could be confirmed. Gelatinous zooplankton in trawls were weighed and volume measured, individuals were identified to genus and counted, and a subsample were weighed.

Acoustic Analysis

Hydroacoustic data were analyzed in EchoView v 7.1 (Myriax Pty Ltd, Hobart, Tasmania, Australia, 2016). Passive noise was estimated from data collected in passive mode (i.e., the echosounder system was receiving but not transmitting while the boat was underway) and removed from the raw data for each transducer (Parker-Stetter et al. 2009). We also applied impulse noise (Ryan et al. 2015) and background noise filters (120 kHz only; De Robertis and Higginbottom 2007) to the data using 5x5 smoothing algorithm and signal to noise ratio of 10. Sounder detected bottom lines were offset by 0.5 m and bottom lines were edited as necessary to remove backscattering from the seafloor. Additionally, the surface exclusion zone included upper 4 m of the water column.

We used a combination of depth and scattering characteristics, Sv threshold and multifrequency dB differencing (Kang 2002, De Robertis et al. 2010) to separate backscatter signal from fish, gelatinous zooplankton (jellyfish, ctenophores, and large predatory medusa), and macrozooplankton. Multifrequency dB differencing of volume backscatter was used to isolate acoustic backscatter characteristic of fish (Fish index = $\Delta s_{v120\text{-}38}$ = -8 to 9.3, De Robertis et al. 2010, Benoit-Bird et al. 2013, Table 1) with a threshold of -60 dB. This relatively strong threshold was necessary to remove the gelatinous zooplankton aggregations, regularly occurred in the upper 50 m of the water column, had similar scattering characteristics on both frequencies (i.e., similar to fish, $\Delta s_{v120\text{-}38}$ = -8 to 9.3) but were weaker scatters than fish. It would also exclude weaker scattering fish, such as larval fish and fish without a swim bladder such as sand lance; however, we rarely encountered sand lance on hydroacoustic transects because schools were typically closer to shore in shallower water than our vessel could sample, which was confirmed by the aerial survey observations (Table 2) and the lack of sand lance in trawls (Table 3). For the gelatinous zooplankton acoustic index we applied an upper and lower threshold of -80 and -60 dB (Table 1), respectively, which is consistent with what is known about the target strength from the main species encountered in trawls (Brierley et al. 2004, 2005). Similarly, acoustic backscatter due to macrozooplankton, which trawl composition suggests was primarily due to euphausiids (or krill, see below), was identified using multifrequency dB differencing (Krill index = $\Delta s_{v120\text{-}38}$ = 9.3-30, De Robertis et al. 2010). Fish and gelatinous zooplankton acoustic indices were integrated from 4 to 125 m (i.e, the maximum depth range of our trawl), and due to their distinct scattering qualities (DeRobertis et al. 2010), krill echointegration exports were made from 30 m to the bottom exclusion line. We chose 30 m as the upper limit because in 2015 the surface zone contained large aggregations of *Clione limacina*, which had the same multi-frequency response as krill. Except for herring (see below), all integration analyses were made at a cell resolution of 100 m horizontal by 5 m vertical.

Table 1. Description of acoustic indices for data collected in Prince William Sound, Alaska, in July 2014-2016. NA indicates not applicable.

Acoustic Index	Frequency (kHz)	Multi-frequency Response (ΔS_v 120-38)	Threshold (dB)	Depth Layer (m)	Fish Species Analysis approach
Fish	120	-8 to 9.3	> -60	4-125	NA
Krill	120	9.3 to 30	> -80	30-bottom	NA
Gelatinous zooplankton	120	-8 to 9.3	-80 to -60	4-125	NA
Herring	38	NA	> -60	4-bottom	Schools detection
Pollock	120	-8 to 9.3	> -60	4-125	Multispecies aggregation
Capelin	120	-8 to 9.3	> -60	4-125	Multispecies aggregation

Echointegration data were used to calculate species-specific acoustic density indices for herring, age-0 walleye pollock and capelin, which together comprised 97-99% of trawl catches. Herring formed discrete schools and are much stronger scatters than age-0 walleye pollock and capelin. Thus we isolated discreet herring schools using the schools detection algorithm SHAPES (Coetzee 2000) using the following detection parameters for individual school characteristics: minimum school length = 5 m, minimum school height = 2 m, minimum candidate length = 1 m, minimum candidate height = 1 m, maximum vertical linking distance = 1 m, maximum horizontal linking distance = 10 m. Herring schools, which appeared as distinct cylinder-like strong scattering schools similar to herring schools described elsewhere (Sigler and Csepp 2007, Boswell et al. 2016) were exported from 38 kHz echograms at 100 m horizontal by 1 m vertical resolution. For each cell we estimated density following the methods of Sigler and Csepp (2007) and Boswell et al. (2016). We accounted for acoustic shadowing and extinction of herring with depth using an extinction correction factor of 1.68, which was calculated from our data following Zhao and Ona (2003). We used the depth integrated expected TS formula: $TS = 20\mathrm{Log}(L) - 2.3\mathrm{Log}(1 + z/10) - 65.4$, where L = total length in cm, and z = depth of cell in herring school. Age classes were assigned through validation of both vessel and aerial observations, and lengths of each age class was determined by the mean of all herring caught in each size class by year (see acoustic validation methods). Age-2+ herring were not encountered during acoustic-trawl surveys in 2016, thus no estimate of age-2+ herring density was attempted for that year (but see Table 2 for aerial school index).

Capelin and age-0 walleye pollock commonly occurred together in trawls, thus we treated them as mixed-species aggregations (Simmonds and MacLennan 2005) after acoustic backscatter due to herring schools was masked from the fish index echograms (i.e., $\Delta S_{v\ 120\text{-}38} = -8$ to 9.3). Capelin were virtually absent from trawls in 2016, thus no estimate of capelin density was attempted in that year. For each transect and year, $\bar{s_a}$ was apportioned by species according to the proportion of capelin and age-0 walleye pollock in the nearest trawl. Species-specific TS formulae for 120 kHz data were applied as follows: $TS_{capelin} = 28.4\ \mathrm{Log}(L) - 81.8$; and $TS_{pollock} = 20\ \mathrm{Log}(L) - 68.9$ (Gauthier and Horne 2004).

Density (ρ) in each cell was estimated using the standard equations $\sigma_{bs} = 10^{\frac{TS}{10}}$, where σ_{bs} is the backscattering cross section, and $\rho = \frac{\bar{s_a}}{\sigma_{bs}}$, where $\bar{s_a}$ is the mean of the area backscattering coefficient (ABC, s_a, m^2m^{-2}). Density was summed across depth layers, averaged across 100 m transect segements, and and finally averaged across transects.

Otoliths

Capelin and sand lance were frozen in the field for otolith measurements in the lab. For both species, age was assigned by counting translucent zones on sagittal otoliths of sand lance. Otoliths were extracted, dried, and examined under reflected light using a Leica M60® dissection microscope. Under reflected light, translucent zones appear dark and opaque zones appear white. Translucent bands forming on the otolith edge were considered incomplete, assuming a January 1 birth date for sand lance (Robards et al. 2002) and capelin (Rottingen and Alvarez 2011). Digital images of each otolith were captured using a Leica DFC425 digital camera. Age assignments for 2016 samples were not available in time for this report.

For capelin, preliminary aging protocols developed by the Institute of Marine Research in Bergen, Norway, were followed (Rottingen and Alvarez 2011). Whole capelin otoliths were submerged in water for approximately one minute prior to age assignment. Capelin otoliths over-clear rapidly and translucent zones may form or widen on the edge very quickly. Age assignments represent the most up to date protocols available, but capelin aging protocols are currently under development worldwide and interpretations are subject to change as additional information becomes available. We examined interannual variation in length at age using analysis of variance and pairwise comparisons (Tukey HSD post hoc test) as sample sizes allowed. We used an α level of 0.05 to determine statistical significance (correct?).

We used ordinary least squares multiple regression to assess weight-length relationships by year for age-1 capelin, age-0 Pacific sand lance and age-1 Pacific sand lance. We did not have a large enough sample size to examine other age classes. We adjusted capelin lengths and weights according to published values for shrinkage due to freezing (Buchheister and Wilson 2005); however, we are not aware of published information on shrinkage due to freezing for sand lance, so we used uncorrected values for this species and expect 2012 and 2013 values to be biased slightly high.

To examine the change in body condition index for each species and age class we fit candidate models that included log-transformed weight (g) as the response and log-transformed length as the predictor using 1) samples pooled across years, 2) differing intercepts by year and 3) differing intercepts and slopes by year. We assessed the best model fit using Akaike's information criteria (AIC).

Objective 3: Distribution and Abundance of Forage Fish Relative to Habitat

To address objective 3, relate abundance and distribution of forage species to abiotic characteristics of the marine environment, we sampled ocean conditions, zooplankton, and nutrients at the end of each trawl or at least once at each sampling station in 2012 – 2016.

We measured oceanographic conditions with a conductivity-temperature-depth profiler (CTD) equipped with a fluorometer, beam transmissometer, photosynthetically active radiometer and dissolved oxygen sensors. CTD profiles were conducted to within 5 m of the seafloor, or to a maximum depth of 300 m. Discrete depth water samples were collected at the surface and 10 m with an watersampler (SeaBird® SBE55) that communicated directly with the CTD. Water for nutrient samples was placed in a 60 ml plastic bottle, frozen in the field, and later analyzed for inorganic nutrient concentrations, including nitrate, nitrite, ammonium, silica, and phosphate, under contract with the University of Washington. Chlorophyll *a* samples from the surface and 10 m depths were filtered onto 25 mm glass fiber fileters, placed in a cryovial and frozen in the field. In the lab we extracted chlorophyll *a* samples in acetone and concentrations were measured with a laboratory fluorometer (Parsons et al. 1984).

Small zooplankton were sampled with a 0.3 m paired ring net with 150 µ mesh on a 50 m (or to 5 m above the bottom) vertical haul. A flowmeter was used to estimate volume filtered through the net. Samples contents were preserved in 3-5 % formaldehyde in seawater solution. In the lab, samples were identified to species (or lowest possible taxon), developmental stage enumerated, and damp dry weights measured to the nearest 0.01 mg (or for organisms weighing over 100 mg, to the nearest mg). Large samples were subsampled with a Folsom plankton splitter after rare organisms were counted and removed. Biomass CPUE (mg m^{-3}) was calculated for each species by multiplying the average weights by the count per tow for each stage by species, summing the weights of all stages for each species, and dividing by the volume filtered.

RESULTS

Results for Objectives 1 and 2 are documented in detail in Appendix A and below.

Systematic Surveys

Our encounter rate with target species at systematically-placed stations throughout PWS in 2012 was not sufficient to assess abundance of target species. Frequency of occurrence (FO) in trawls was low for capelin (3.7%), eulachon (3.7%), Pacific sand lance (0%), and euphausiids (11.1%). Likewise, beach seines targeting Pacific sand lance had low and variable catches (mean CPUE ± SD = 3.5 ± 10.5 fish per set). Thus, we largely abandoned the systematic survey and explored ways to improve our ability to sample target fish species.

Aerial-Acoustic Surveys

Validation of Aerial Observations

In 2014-2016, we validated 34 schools during July. The aerial observation identified one school as capelin, 25 schools as herring, and 8 schools as sand lance. Herring schools were correctly identified to species 84% of the time (21/25 schools) and sand lance schools were correctly identified 88% (7/8) of the time. The one school that was classified as capelin was composed of age-0 herring.

During the 2014-2016 validation of aerial observations there were 15 herring school observations where age of fish in schools was classified from the airplane and the vessel. Adult herring and age-0 herring schools were identified correctly by aerial observers 100% (6/6 and 2/2 schools, respectively) of the time; however, age-1 herring were identified correctly only 43% (3/7 schools) of the time. Misclassification of age-1 herring schools were verified as age-0 herring schools 75% (3/4 schools) of the time. Additionally, one misclassified age-1 herring school was composed of a mix of age-1 and age-2+ herring.

Thus, validation efforts suggest herring and sand lance schools can be classified to species by aerial observers. Additionally, adult herring schools were always classified correctly; but smaller age-classes (i.e., age-0 and age-1) of herring could not be reliably distinguished from one another and were therefore combined as juvenile herring for our work conducted in July.

Aerial Schools Index

The July 2014-2016 random stratified aerial block surveys yielded overall mean (95% CI) aerial school index of 852 (402-1796) schools in 2014, 1607 (976-2476) schools in 2015 and 1506 (637-4442) schools in 2016. Confidence intervals were overlapping and suggest high variability in the schools index such that no difference was detected in log-transformed aerial school indices among years ($\mathrm{ANOVA}_{[df:2,\ 287;\ F\ =\ 2.5]}$ $p > 0.05$). The proportion of schools classified as juvenile herring (range: 69-79%) was greater than for adult herring (range 3-10%) or sand lance (range: 12-28%) (Table 2). Unidentified schools made up an average of 3% of schools in all years (range: 1-4%).

Table 2. Aerial survey effort (n = number of grid cells sampled), total area surveyed, raw counts of schools observed by species, and aerial school index (number of schools) by species, in Prince William Sound, Alaska.

			School Counts				Aerial School Index			
Year	n	Area (km^2)	All Schools	Juvenile Herring	Adult Herring	Sand Lance	All Schools	Juvenile Herring	Adult Herring	Sand Lance
2014	107	2819.3	447	354	24	49	852 (402-1796)	666 (249-1584)	50 (10-136)	90 (42-389)
2015	83	2083.6	519	396	41	62	1607 (976-2476)	1150 (647-1897)	157 (14-452)	204 (20-665)
2016	98	2502.2	672	464	16	189	1506 (637-4442)	872 (420-2205)	49 (3-242)	582 (137-2820)

Acoustic Indices

We used multi-frequency acoustic analyses to generate several acoustic indices (see Table 1), and for target forage fish species we also provide species-specific density indices (Table 3). Krill and gelatinous zooplankton composition in trawls is also discussed below.

Acoustic fish density index (i.e., all fish at 120 kHz, Table 1) was below average in 2015 and above average in 2014 and 2016 (Fig. 2). Gelatinous zooplankton index was higher than average in 2015, while the krill index was below average in 2014 and 2015, and above average in 2016.

Species-specific acoustic fish density indices suggest differences between age-0 and age-1 herring vs. age-0 pollock and capelin (Table 2, Fig. 3). Juvenile herring acoustic density indices were highest in 2015, which concurs with the aerial schools index (Table 2). In 2015 age-0 walleye pollock acoustic density indices were lowest of the study (Table 3, Fig. 3). Highest estimates of acoustic density indices for age-0 walleye pollock were observed in 2016 (Fig. 3). Capelin densities were three-orders of magnitude lower than pollock in 2014 and 2015, and the distribution of capelin was more patchy than walleye pollock (Appendix A). Only a single capelin was captured in a trawl in 2016, suggesting that capelin density was too low to quantify, so estimates of capelin density were not available in that year.

Based on trawl compositions (proportion of biomass weighted by effort), macrozooplankton assemblages were primarily composed of a mix of euphausiid species (99% in 2014, 100% in 2015), including *Euphausia pacifica*, *Thysanoessa inermis, T. raschii*, and *T. spinifera* (Fig. 4). Although all species were represented in 2014, the euphausiid community composition changed to one dominated by *T. spinifera* and *E. pacifica* in 2015. Due to a sample preservation issue, species-specific biomass could not be quantified in 2016; however, the presence of *T. spinifera* in two trawls, and a mix of *T. spinifera* and *E. pacifica* in one trawl was confirmed.

Gelatinous zooplankton in trawl catches was generally composed of *Aequorea*, *Aurelia*, *Chrysaora*, *Cyanea*, *Phacellophora*, and *Pleurobrachia*, and their composition varied by year (Fig. 5). In addition to high acoustic biomass of this group in 2015, the zooplankton community was dominated by *Aurelia* (moon jellies) rather than *Aequorea* (water jellies) as it was in 2014 and 2016. Additionally, there was an apparent influx of the ctenophore *Pleurobrachia* in 2015, which comprised a greater proportion of the biomass compared to 2014 or 2016.

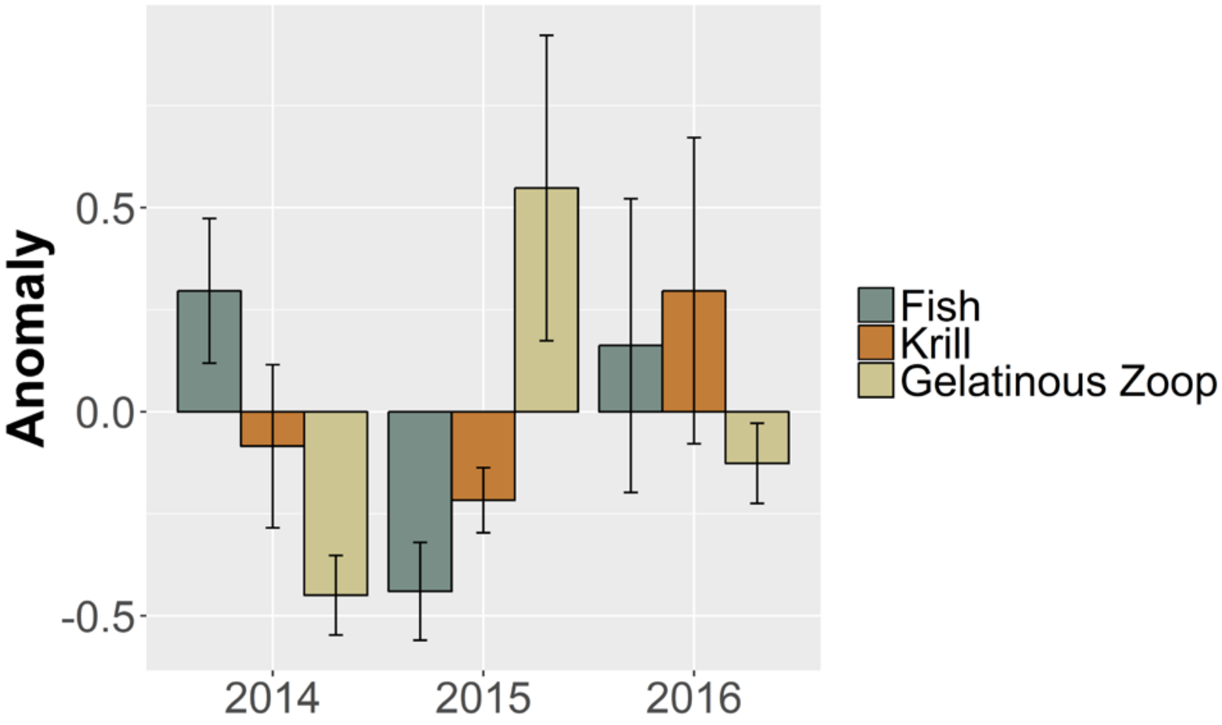

Figure 2. Interannual variability in mean (± 1SE) acoustic indices during July in Prince William Sound, Alaska. Acoustic indices were derived from 120 kHz hydroacoustic data (s_a, area backscattering coefficient, m^2 m^{-2}) using a combination of multi-frequency response and density criteria. Indices were scaled to a mean of 0 and SD of 1 to facilitate plotting on a common scale.

Table 3. Mean (95% CI) species-specific indices of acoustic density (fish m^{-2}) of forage fish in Prince William Sound, Alaska.

Year	Age-0 walleye pollock	Capelin ($x10^{-3}$)[a]	Age-0 herring	Age-1 herring	Age-2+ herring
2014	0.013 (0.007-0.020)	0.024 (0.012-0.041)	0.036 (0-0.107)	0.029 (0-0.086)	0.055 (0.007-0.152)
2015	0.003 (0.002-0.007)	0.004 (0-0.016)	0.194 (0-0.582)	0.049 (0.012-0.134)	0.016 (0-0.047)
2016	0.024 (0.010-0.057)	NA[b]	0.018 (0-0.055)	0.023 (0-0.075)	NA[b]

[a] Capelin acoustic density was lower than other species, and thus is scaled by 10^{-3}

[b] Capelin and age-2+ herring were not sampled on acoustic transects in 2016, although these species were not absent from the region, density estimates were not attempted in that year due to lack of data during surveys

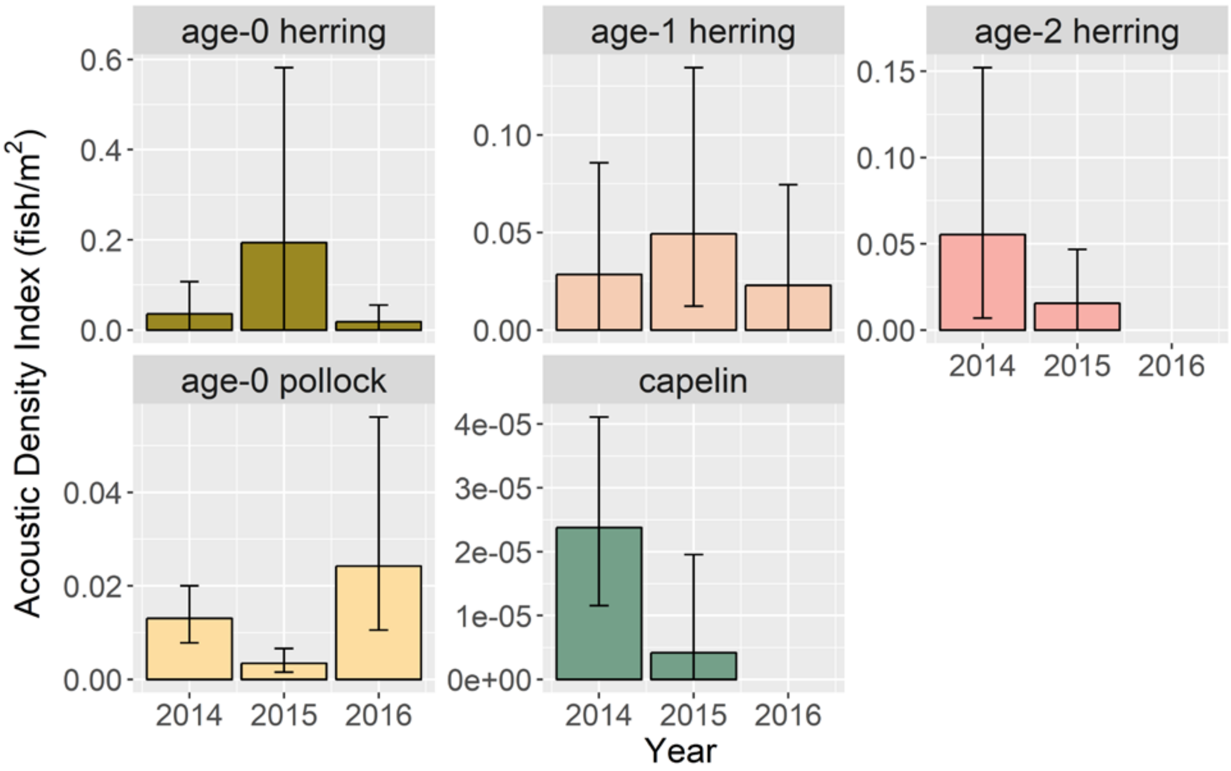

Figure 3. Mean (± 95% CI) species-specific acoustic density indices of forage fish in Prince William Sound, Alaska. Due to their different scattering characteristics and schooling behavior, herring were analyzed as discrete schools (38 kHz), while pollock and capelin were analyzed as mixed-species assemblages (120 kHz). Note differing scales on the y-axis. In 2016, capelin and age-2+ herring were not encountered during acoustic-trawl surveys in high enough numbers to estimate densities.

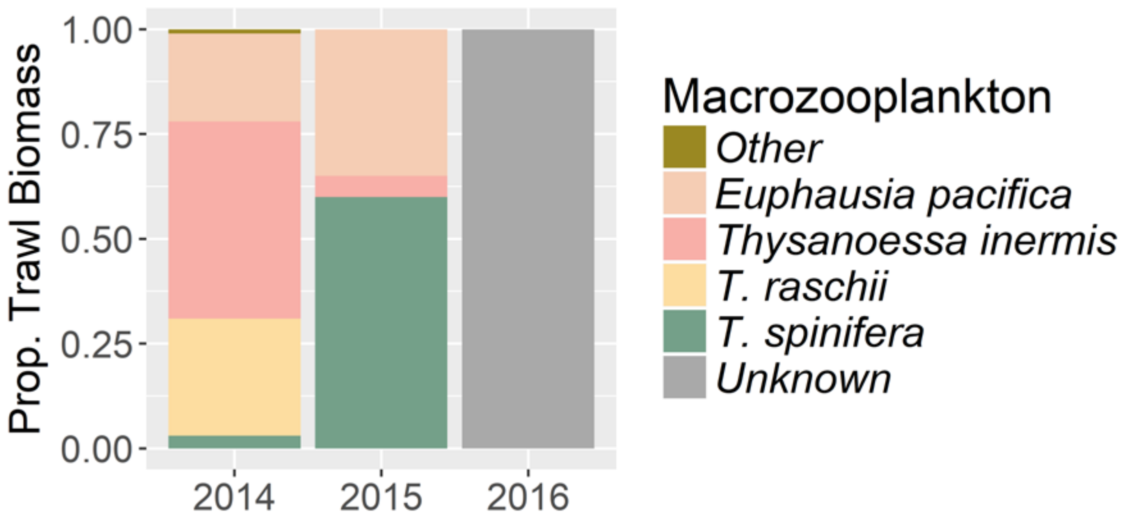

Figure 4. Composition of macrozooplankton in trawls, expressed as the proportion of total biomass by species in trawl samples and weighted by effort. Note, trawl samples in 2016 could not be quantified to species by biomass, however, *T. spinifera* (n = 3) and *E. pacifica* (n = 1) were present.

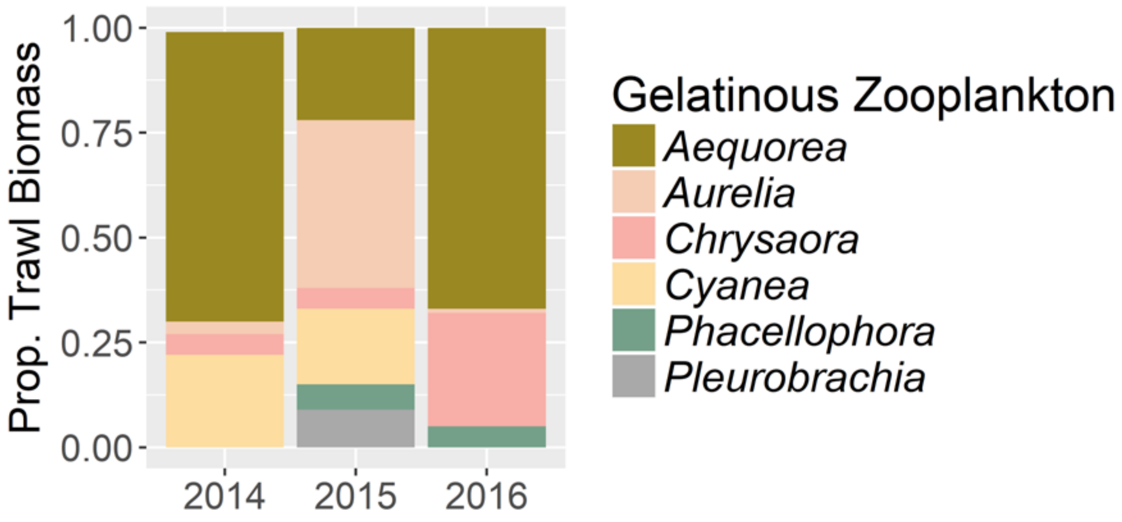

Figure 5. Composition of gelatinous zooplankton, expressed as proportion of total biomass in trawls and weighted by effort.

Fishing Effort and Catches

We caught 198,133 fish with 167 deployments of seven types of fishing gear (Table 4) during summers in 2012 – 2016 (Fig. 4). Several large purse seine catches targeting sand lance schools caught 66 % of the fish, and modified herring trawls caught 32 % of the total catch. Jigs, which were primarily used to validate size and species when we encountered strong acoustic sign, caught the fewest fish but they were effective at quickly verifying size and species of forage fish aggregations that would otherwise be difficult to catch with other means, particularly Pacific herring and walleye pollock. On the other hand, trawls were more effective for catching young of the year walleye pollock and immature capelin. Beach seines were less effective than purse seines at catching target species (Table 4).

Fishing effort was not always conducted in the same place each year (Fig. 4), thus CPUE data from trawls in each year provide only a relative index of abundance for forage species (Table 5). Still, these data provide the context for changes observed in PWS across all years of the study that may be consistent with Gulf-wide trends. Capelin CPUE was highest in 2013 and lowest in 2016. Age-0 pollock CPUE index was highest in 2012 and lowest in 2015. Herring CPUE was highest in 2012, driven mainly by young of the year herring, and consistent with a strong year class that was again observed in 2013. Eulachon were rarely caught in the trawl, except near tidewater glaciers, thus we were unable to adequately monitor them using the methods we employed.

Table 4. Effort (number of hauls), catch (number of fish), catch by species, and percent of catch that was comprised of non-target species by fishing method during July forage fish surveys 2012 - 2016 in Prince William Sound, Alaska.

Fishing Method	Effort	Catch	Capelin	Herring	Sand lance	Eulachon	Walleye pollock	Other
beach seine	28	2324	0	399	66	0	226	70.3
cast net	10	1216	990	134	61	0	25	0.5
dip net	8	1759	98	1443	218	0	0	0
gill net	2	47	0	3	36	0	0	17
jig	47	154	0	101	13	0	21	12.3
modified herring trawl	65	62585	203	1336	0	36	56809	6.7
purse seine	7	130048	0	38	127976	0	1909	0.1
Total	167	198133	1291	3454	128370	36	58990	3

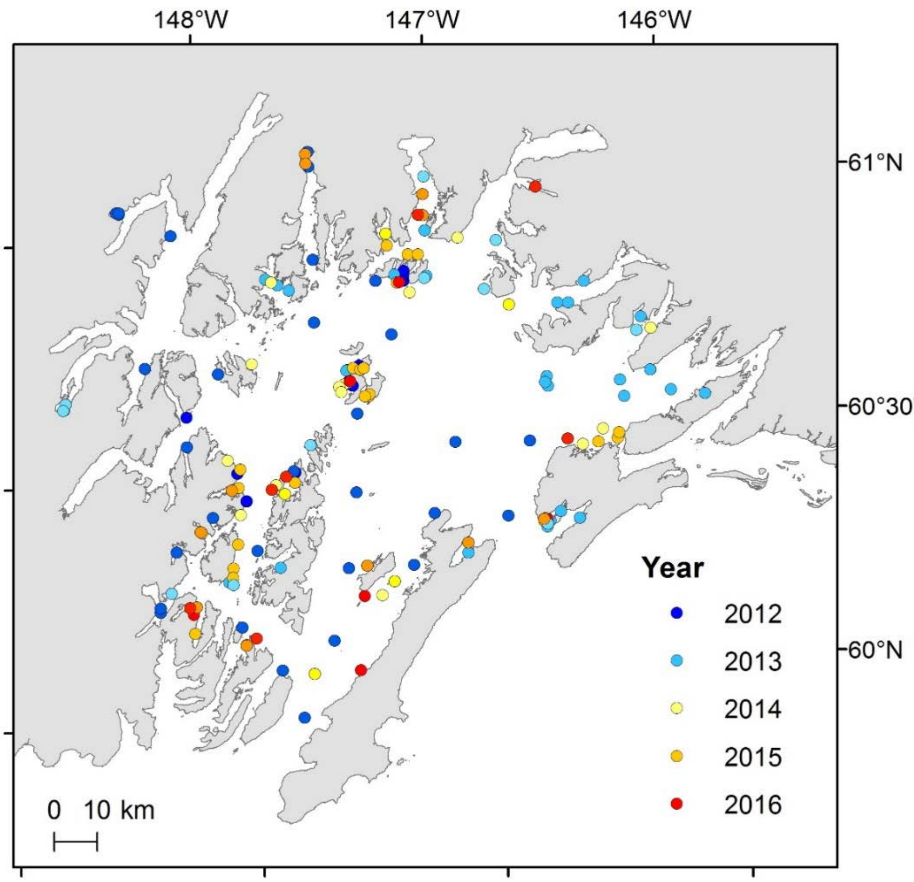

Figure 6. Distribution of fish sampling effort by year. Prince William Sound, Alaska.

Table 5. Mean (1SE) catch per unit effort (number of fish km^{-1}) for forage species in midwater trawls conducted in July 2012 - 2016 within Prince William Sound, Alaska. n = number of trawls, age-0 pollock includes fish with total length < 100 mm.

Year	n	Capelin	Age-0 Pollock	Herring	Eulachon
2012	31	1.79 (0.79)	3825.49 (3511.60)	26.27 (24.42)	0.63 (0.29)
2013	12	3.05 (1.40)	127.95 (86.70)	3.98 (2.06)	0.03 (0.03)
2014	5	2.77 (2.02)	1956.97 (1912.10)	0.37 (0.23)	0.08 (0.08)
2015	11	1.44 (0.72)	23.72 (19.80)	3.53 (2.70)	0.26 (0.17)
2016	7	0.09 (0.09)	268.43 (185.90)	0.19 (0.19)	0

Body Condition of Capelin and Pacific Sand Lance

Sand lance age assignments ranged from age-0 to age-2 (n = 400). The otoliths of age-0 sand lance were very opaque and easily distinguished from other age classes (Fig. 7). Age-0 and age-1+ sand lance tended to separate by length with age-0 fish being <100 mm; however, sand lance <100 mm did include some age-1 individuals and would result in a misclassification of 8% of age-1 individuals (Fig. 8). Some interannual variability in length at age was apparent. Age-0 sand lance collected in 2012 were larger than those collected in any other year ($P < 0.05$). The length of age-1 sand lance was smallest in 2015 compared to any other year ($P < 0.05$). Age-2 sand lance were not encountered in each year, which prevented interannual comparisons (Fig. 8).

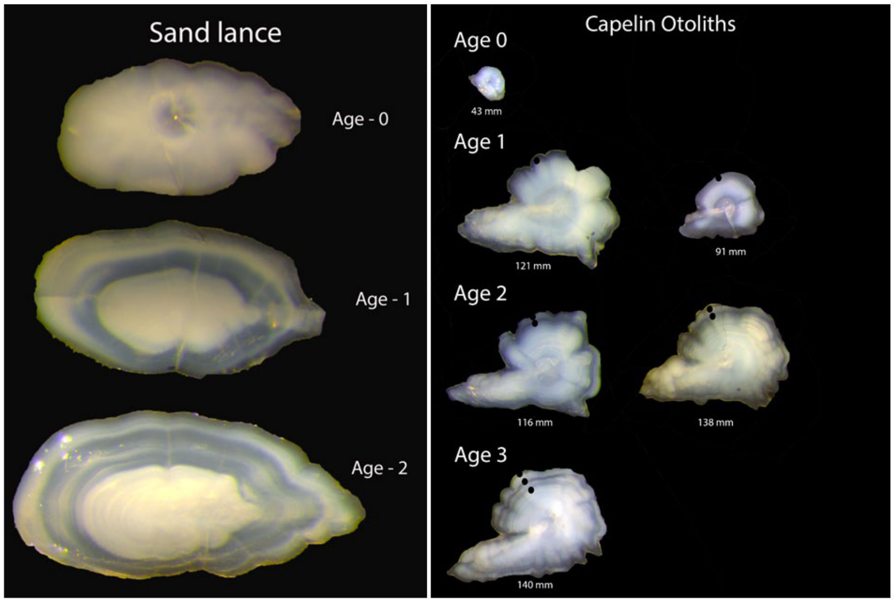

Figure 7. Otolith aging key. (Left) Sand lance sagittal otoliths of age-0, age-1, and age-2 fish. (Right) Capelin sagittal otoliths of age-0, age-1, age-2, and age-3 fish. Capelin length at capture noted below each otolith image.

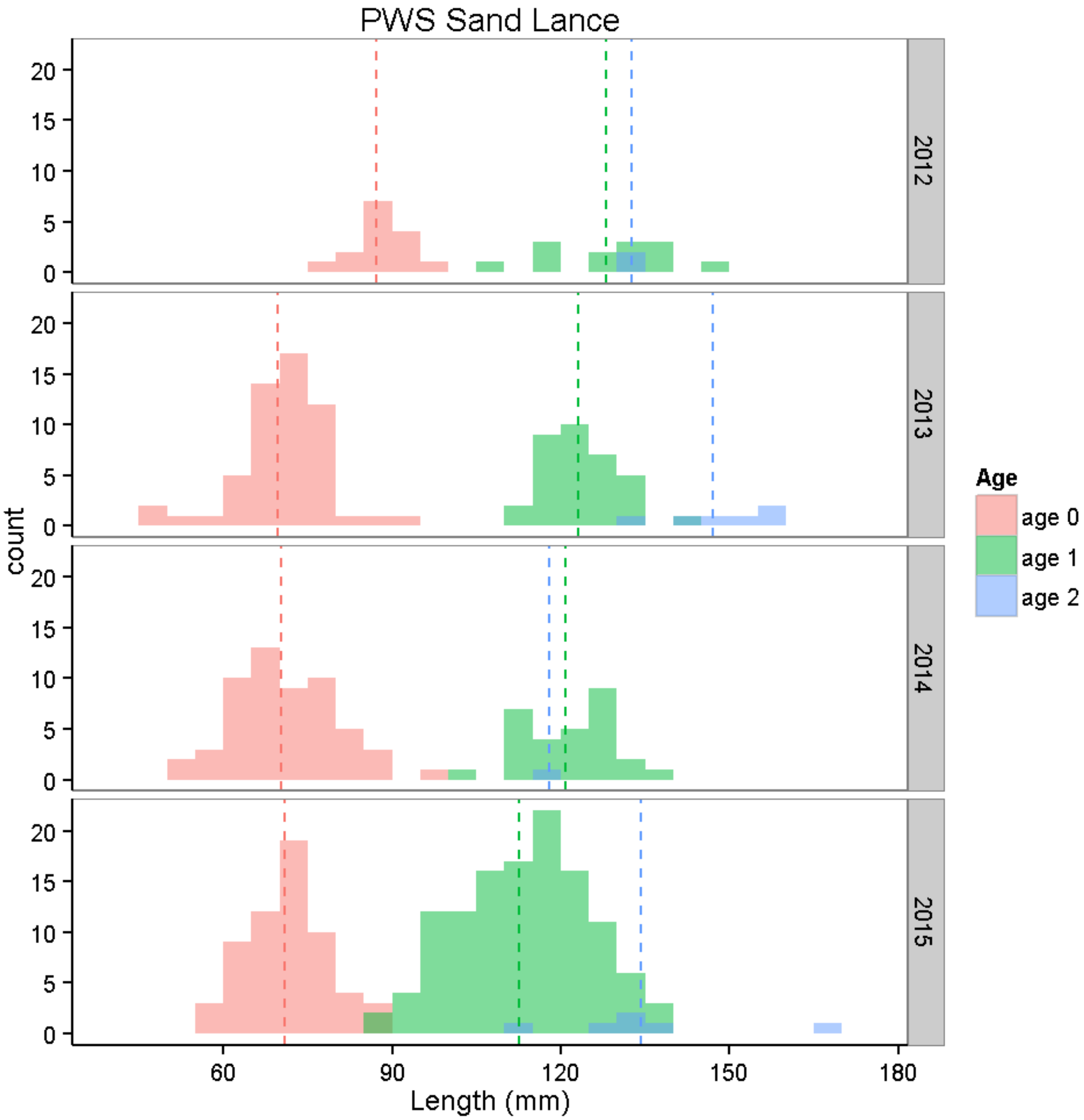

Figure 8. Length distribution (bars) and mean length-at-age (dashed vertical lines) of Pacific sand lance captured in Prince William Sound, Alaska, 2012-2015. For age-0 fish, individuals collected in 2012 were larger than those collected in any other year. The length of age-1 fish was smaller in 2015 than any other year. Among age-2 fish, sample sizes were too low for comparisons among years.

Capelin age assignments ranged from age-0 to age-3 (Fig. 7), with more than 85% of fish collected estimated to be age-1 (n=169 of 198 individual). The 2012 length distribution of age-1 fish was bimodal and did suggest that there could be two peaks in spawning time corresponding to the two peaks in length size (Fig. 9). Age could not be predicted from capelin length, despite the field observation of distinct length classes and the common practice of assigning age based on size of capelin, thus we do not recommend assigning capelin age based on size. The few age-0 capelin sampled during this study were used only to assist with confirming otolith aging protocols.

The few age-2 and age-3 individual capelin captured were primarily encountered in 2013 and were in spawning condition. On July 2, 2016 we encountered a large spawning aggregation of capelin in Port Etches (60°20.3016’ N, 146°41.0226’ W), near the Hinchinbrook Entrance, however, the data from otoliths of fish collected there were not available at the time of this report.

The length of age-1 capelin did vary across years with larger age-1 fish captured in 2015 compared to any other year and larger fish in 2012 compared to 2014. It is important to note that many more capelin were encountered in 2012 as compared to 2015 (Fig. 9). The few capelin captured in 2015 were exclusively found in the thermal refuge of glacially influenced embayments in Unakwik Inlet and near the Columbia Glacier. Thus, 2012 was characterized by many large age-1 capelin and 2015 was characterized by few large age-1 capelin.

Length-weight

Capelin and sand lance length-weight relationships differed by year in 2012-2015 (Table 6). Information criteria suggested the best fit model predicting log-transformed weight of age-1 capelin included log-transformed length (mm) and year as main effects ($\text{OLS}_{[\text{df: }4,\ 159;\ \text{F: }369.2]}$ $R^2 = 0.90$, $p < 0.001$). The change in intercepts for each year suggested that weight at length was greatest in 2013 and lowest in 2015. After back-transformation, model predictions made at the median length of age-1 capelin (91 mm) suggest 2012, 2014, and 2015 weight at length was 9 %, 18 %, and 33 % lower than in 2013, respectively.

Akaike Information criteria indicated the best fit model predicting log-transformed weight of age-0 sand lance in 2012-2015 included an interaction between log-transformed length and year predictors (Table 6), such that both the intercept and the slopes or the relationship for each year differed ($\text{OLS}_{[\text{df: }7,\ 178;\ \text{F: }534.8]}$ $R^2 = 0.95$, $p < 0.001$). Back-transformed predictions for each year of an 86 mm fish, i.e., the mode of age-0 sand lance lengths sampled in 2012 but well within the range of sampled lengths in all years (Fig. 8), the predicted difference in weight at length was greatest in 2012 and lowest in 2015. Weight of an 86 mm fish in 2013, 2014 and 2015 was predicted to be 9%, 28% and 35% lower than it was in 2012.

Similarly, the best fit model for age-1 sand lance included an interaction between log-transformed length and year predictors (Table 6) ($\text{OLS}_{[\text{df: }7,\ 179;\ \text{F: }471.3]}$ $R^2 = 0.95$, $p < 0.001$). At 117 mm length, which is the median age-1 sand lance length of all years (Fig. 8), predicted weights were highest in 2012 and lowest in 2015. Predicted weights at median length in 2013, 2014, and 2015 were 3%, 17%, and 20% lower than in 2012.

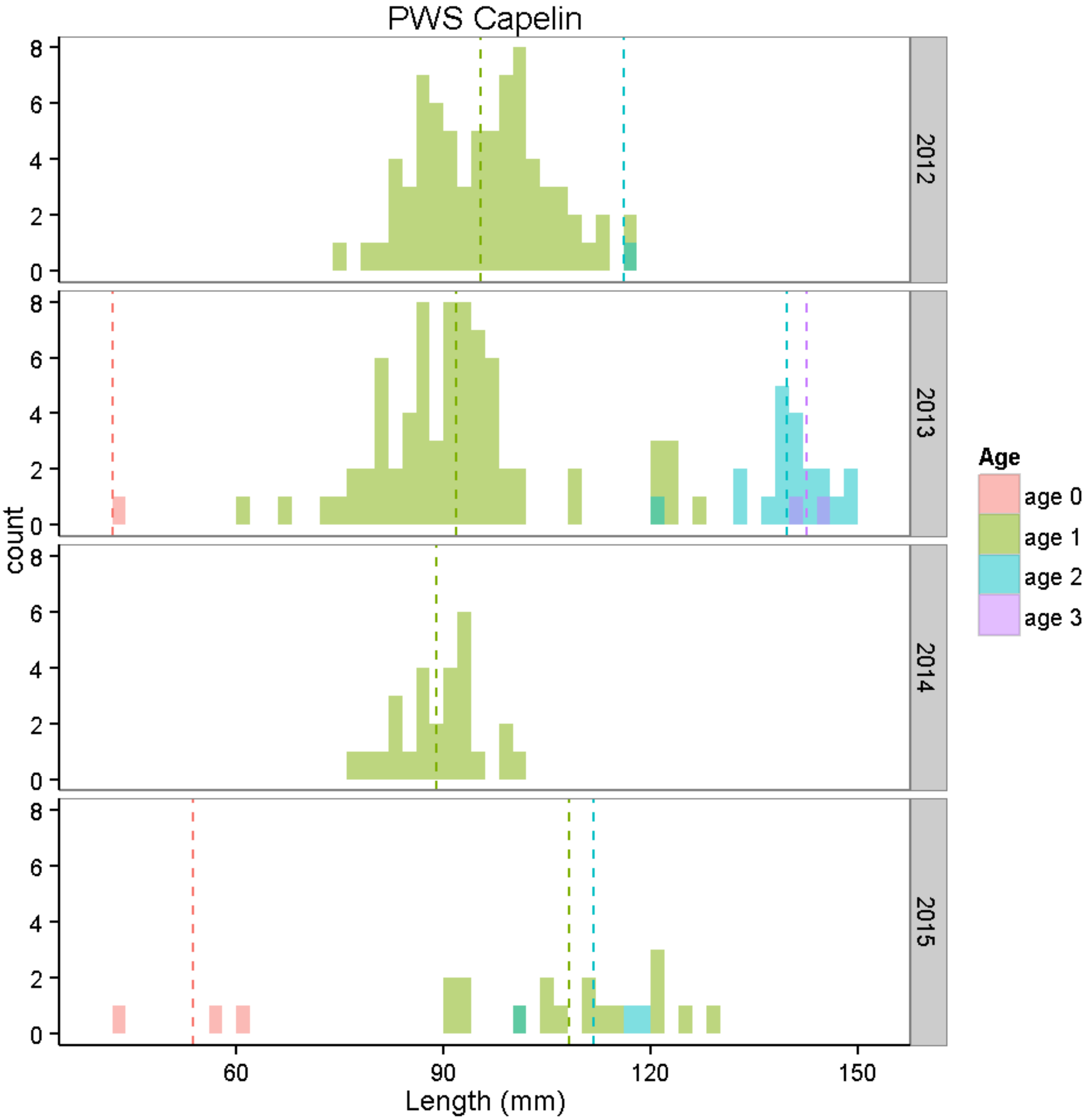

Figure 9. Length distribution (bars) and mean length-at-age (dashed vertical lines) of capelin captured in Prince William Sound, Alaska, 2012-2015. Colored bars and dashed lines denote age classes: age-0 (pink), age-1 (green), age-2 (blue), and age-3 (purple). The length of age-1 fish differed across capture years with larger individuals in 2015 compared to any other year and larger fish in 2012 compared to 2014. Note: Very few age-1 capelin were captured in 2015.

Table 6. Model selection Akaike information criteria (ΔAIC) and best model coefficients for weight at length relationships of capelin and sand lance in Prince William Sound, Alaska during summers 2012 - 2016. Model 1 pooled all years, model 2 allowed intercepts to differ by year but assumed the slope of the relationship, and model 3 allowed the intercepts and slopes to differ each year. Asterisks indicate significance: *** $p < 0.001$, ** $p < 0.01$ and *$p < 0.05$, NA indicates not applicable.

		ΔAIC	
Model	Capelin Age 1	Sand lance Age 0	Sand lance Age 1
1) log(weight) ~ log(length)	55.20	112.06	97.35
2) log(weight) ~ log(length) + Year	0	16.40	4.07
3) log(weight) ~ log(length) x Year	2.14	0	0
Best model fit	$R^2 = 0.90$***	$R^2 = 0.95$***	$R^2 = 0.95$***
		Best Model Coefficients	
Intercept	-15.31956***	-9.1458***	-15.8758***
log(length)	3.64587***	2.2300***	3.7186***
Year - 2013	0.08968***	-5.3865*	1.7275
Year - 2014	-0.07473*	-6.4776**	0.8323
Year - 2015	-0.19836***	-3.1679	3.3573*
log(length) x Year 2013	NA	1.1906*	-0.3707
log(length) x Year 2014	NA	1.3988*	-0.2087
log(length) x Year 2015	NA	0.6444	-0.7440*

Distribution and Abundance of Forage Fish Relative to Habitat

We measured changes in the corresponding habitat conditions within the acoustic survey area in 2014-2016 (Fig. 10). Copepod and phytoplankton (i.e., chlorophyll *a*) indices were lowest in 2015, and this may have been a primary influence in the lower body condition of capelin and sand lance we observed in that year. In contrast to 2014 and 2016, when higher than average chlorophyll *a* concentrations corresponded with lower than average nitrate (suggesting nutrient drawdown), in 2015 below average chlorophyll *a* concentrations occurred with higher than average nitrate concentrations (suggesting low nutrient demand). Stratification in the upper 10 m of the water column was above average in 2015, which also coincided with above average temperatures in the water column above 125 m (i.e., the maximum depth we could sample fish with the trawl). The years between 2014 – 16 were anomalously warm in the Gulf of Alaska (Di Lorenzo and Mantua 2016). Our data collected in conjunction with acoustic surveys in July suggest 2015 water column conditions were warmer than 2014 or 2016 in the inshore waters of PWS (Fig. 10).

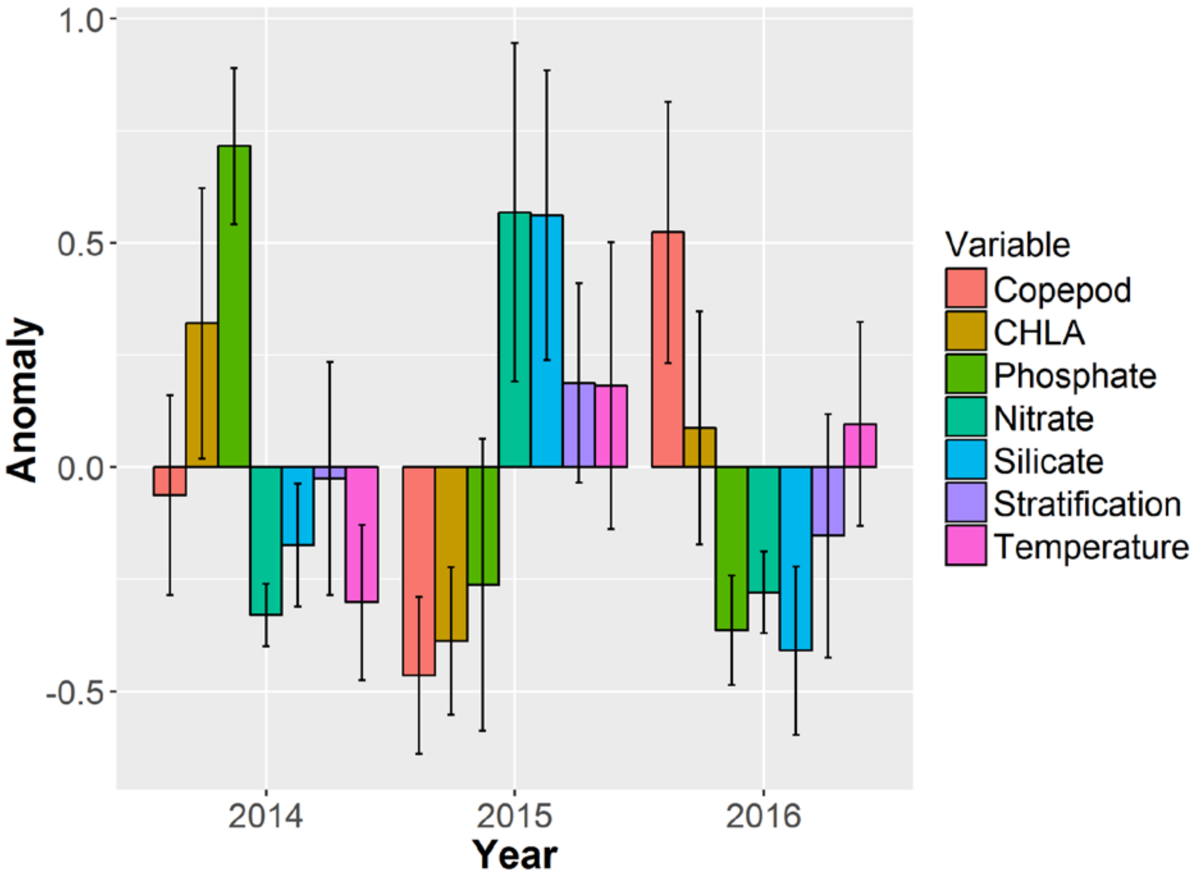

Figure 10. Habitat indices measured during July forage fish acoustic surveys in Prince William Sound, Alaska. Variables, including copepod biomass (mg m-3), extracted chlorophyll a concentration at 10 m (CHLA, ug L^{-1}), nutrients at 10 m (uM), stratification (average $\Delta\sigma t < 10$ m) and average temperature (°C, < 125 m) were scaled to a mean of 0 and SD of 1 to facilitate plotting on a common scale, and to visualize relative changes among years. Error bars represent ±1 SE.

DISCUSSION

We observed changes in forage fish abundance and body condition coincident with anomalously warm ocean conditions that occurred in the region during 2014-2016. Age-0 pollock and capelin acoustic indices were lowest in 2015, but juvenile herring aerial and acoustic indices were highest in 2015. Sand lance aerial schools index was highest in 2016, and validation of these schools indicate these fish were primarily < 100 mm in length. Condition of capelin and sand lance was lowest in 2015. Furthermore, acoustic indices of krill were lowest in 2015 and highest in 2016.

Capelin became scarce in the coastal waters of PWS in 2014-2016 which agrees with studies of seabird diets during the same time (Hatch 2016). These observations reflect a protracted distribution, lower density, and lower body condition of capelin, particularly in 2015. Although we encountered a single spawning aggregation of capelin on July 2, 2016 in Port Etches, frequency of occurrence (3%) and CPUE of capelin in trawls during 2016 were the lowest of all years despite sampling effort in deeper water and thermal refuges where they typically occur. Capelin are a cold water species known to respond rapidly to warming temperatures (Rose 2005). Similarly, for sand lance we observed lower body condition in warm years (2014 and especially in 2015) compared to cooler years (2012 and 2013).

In the Gulf of Alaska, warm conditions have been associated with better outcomes for sand lance and cool conditions are associated with better conditions for capelin (Anderson and Piatt 1999, Sydeman et al. 2017). The abundance of sand lance has been positively related to interannual and spatial variation in sea surface temperature within Gulf of Alaska nearshore habitats (Litzow et al. 2002) and somatic growth has been positively related to temperature across years (Robards et al. 2002). Lower body condition of sand lance in PWS, especially in 2014 and 2015, and long-term data from Middleton Island indicate lower contributions of sand lance to predator diets despite warm conditions (Hatch 2016). These findings suggest the recent anomalously warm ocean temperatures may have been associated with unfavorable conditions for sand lance.

Overall, we observed few age-classes for sand lance and capelin captured in PWS during July. Among sand lance, the majority of individuals were age-0 (47%) or age-1 (49%) and very few individuals were age-2. Our results are similar to those observed in shallow-water habitats of southeastern Alaska where age-0 and age-1 sand lance also dominated catches (Johnson et al. 2008). In contrast, sand lance in Cook Inlet, Alaska spanned seven age classes at capture (age-0 to age-6) and larger spawning fish have been observed in the fall/winter (Robards et al. 2002).

Many patterns we observed during sampling in PWS were consistent with patterns of recruitment, abundance and/or body condition of forage fish in the larger northern Gulf of Alaska region. For example, young of the year walleye pollock were extremely abundant during our surveys in 2012 and least abundant in 2015, which is consistent with changes in Gulf-wide recruitment and biomass (Dorn et al. 2016). We found capelin had highest body condition in 2013, which was a year when capelin were widespread and abundant on Gulf of Alaska Integrated Ecosystem Research Program acoustic-trawl surveys (McGowan et al. 2016). Time series data from Middleton Island show that after several years of high frequency of occurrence in seabird diets in 2008 – 2013, capelin virtually disappeared from diets in 2014-2016 (Hatch 2016). Similarly, the Gulf-wide capelin index based on predator diets showed increasing trends beginning in 2006 but declined beginning in 2014 (Zador and Yasumiishi 2016). PWS provides spawning and nursery habitat for capelin (Brown 2002, Brown et al. 2002), and the rapid response of this important forage species to changes in ocean temperature (Rose 2005) make it a key species for monitoring of marine ecosystem conditions into the future.

We also observed changes in forage fish prey (copepods and krill), phytoplankton (chlorophyll *a*), and the physical habitat in PWS during 2014-2016. The lower body condition of capelin and sand lance in 2015 co-occurred with low copepod biomass, low chlorophyll a concentrations, and warm water column temperatures. We also observed a change in community composition of both krill and gelatinous zooplankton in 2015. Our data suggest that lower and mid-trophic level productivity was reduced during anomalously warm ocean conditions in PWS. These results help understand the causes and consequences of ecosystem-wide changes in the Gulf of Alaska associated with the recent marine heatwave in the northeast pacific.

CONCLUSIONS

Our objectives in this study were to determine robust indices to monitor changes in forage fish, and to document the current distribution, abundance, body condition, and habitat of forage species in PWS. We tested a variety of methods to complete these objectives. Our original approach included a random systematic sampling design but was discontinued because the effort was concentrated in poor forage fish habitat and frequency of occurrence of target species on surveys was too low to adequately describe distribution or abundance. Beginning in 2014, we tested an approach that combined aerial surveys and acoustic-trawl surveys, using existing aerial shoreline data on school distribution and persistence to identify density strata within the study region. We found this method more useful than the systematic design because it targeted more suitable habitat for the most common species of forage fish, and would provide adequate indices for documenting population changes.

The aerial-acoustic survey design implemented in this study allowed us to evaluate the utility of a combined approach. The use of aerial and acoustic methods together provided a means to measure inshore shallow habitats unsuitable for vessel-based acoustic surveys as well as deeper habitats unsuitable for aerial surveys. Due to the shallow coastal distribution of schooling fish in summer, aerial shoreline surveys in June provide a useful and cost-effective index of forage fish abundance of some species in PWS. With proper validation of observations, tracking this index annually could be especially useful for juvenile herring as it may inform the age-structured assessment used to estimate the herring population for fisheries management. Likewise, for sand lance, a species that regularly occurs in water that is too shallow to reliably measure with acoustics but is easily observed from an airplane, aerial surveys provide a cost-effective means to track an index of abundance over time. Acoustic-trawl surveys provided quantitative indices of density for herring, pollock, and capelin, the most commonly encountered forage species in PWS. Aerial surveys were important for providing an index for age-2+ herring schools that year, and the return to the known spawning location for capelin at Hinchinbrook Entrance was important in providing data for capelin in that year. Multi-frequency acoustic surveys are a preferred survey method for assessing macrozooplankton species such as krill (De Robertis et al. 2010, Ressler et al. 2012). None of the survey methods we applied were successful at monitoring eulachon, which may be better assessed at their spawning grounds in spring.

Although we recommend aerial-acoustic methods as a robust means to monitor forage fish populations trends in PWS, the survey would still be a costly and logistically complicated program to sustain over time. Directed funding to support the aerial survey component under the Herring Research and Monitoring program was discontinued in 2017. Furthermore, the Gulf Watch Alaska principal investigators collectively agreed that integration within the pelagic ecosystem component was important in moving forward with the forage fish component and we identified the need for tighter seasonal and spatial coupling of the predator and forage fish (i.e., prey) monitoring. Furthermore, due to the relative ease and efficiency that information from a predator diet component can provide, there was consensus within the Gulf Watch Alaska program to support the long-term seabird diet data collection effort at Middleton Island (Hatch 2013, 2016).

Therefore, in 2017-2021, the Gulf Watch Alaska forage fish project will target fall sampling of whale and seabird foraging aggregations, as well as dedicated support to continue the Middleton Island seabird diet data collection effort. Despite our revised sampling effort, we expect to continue some key indices, for example, sand lance collections may be possible though collaborations with ongoing studies, as well as acoustic density indices in fall. Continued monitoring will help determine the duration of impacts on forage fish abundance and body condition, and understand the potential prolonged impacts of marine heatwaves to the PWS and Gulf of Alaska ecosystems.

ACKNOWLEDGEMENTS

Funding was provided by the *Exxon Valdez* Oil Spill Trustee Council and U.S. Geological Survey Alaska Science Center. We thank Greg Snedgen, the captain of the USGS *Alaskan Gyre*, as well as Jonathan Felis, Jamie King and Mike Larson for their help in the field. We also appreciate Scott Pegau (Prince William Sound Science Center, Herring Research and Monitoring Program) and Mike Collins for their tireless efforts conducting aerial surveys. Chris Stark (Stark Fisheries Research) processed zooplankton and euphausiid samples, and Kathy Krogslund (University of Washington Marine Chemistry Lab) processed nutrient samples. Any use of trade, firm or product names is for descriptive purposes only and does not constitute endorsement by the U.S. government. All capture and handling procedures were reviewed and approved by the USGS Alaska Science Center Animal Care and Use Committee (number 2012-4). The views expressed here are our own and do not necessarily reflect those of the *Exxon Valdez* Oil Spill Trustee Council.

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APPENDIX A: SCIENCE SYNTHESIS CHAPTER – FORAGE FISH POPULATIONS IN PRINCE WILLIAM SOUND: DESIGNING EFFIECIENT MONITORING TECHNIQUES TO DETECT CHANGE

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Introduction

Forage species of Prince William Sound (PWS) are an important node in marine food webs of the Sound because they link primary and secondary producers with higher trophic levels. Forage species typically produce a large number of offspring and have short life spans, and these traits predispose populations to large fluctuations in abundance, with subsequent impacts on predators. Examples of important forage taxa in PWS include capelin (*Mallotus villosus*), Pacific sand lance (*Ammodytes hexapterus*), juvenile walleye pollock (*Theragra chalcogramma*), eulachon (*Thaleichthys pacificus*), Pacific herring (*Clupea pallasii)* and euphausiids (Euphausiacea), all included hereafter under the label of "forage fish".

In 1999, the Fishery Management Plan for the Ground fish Fishery adopted amendments 36 and 39 for the Bering Sea/Aleutian Islands and Gulf of Alaska, respectively, that prohibited a directed commercial fishery on species known to be important (excluding Pacific herring and walleye pollock) for supporting healthy populations of higher trophic organisms such as marine mammals, seabirds, and commercially important fish. In contrast to commercial fish species that require regular stock assessments for management purposes, standardized methods for monitoring forage fish in Alaska are not well established in any region (Ormseth 2014). This is due in no small measure to the patchy distribution of schools, high mobility, and differing life histories among the various species of interest. In short, forage fish are difficult to study. Several different approaches have been employed in PWS and the Gulf of Alaska region in recent decades with varying degrees of success.

In response to an initial lack of recovery of wildlife populations following the *Exxon Valdez* Oil Spill (EVOS) (Peterson et al. 2003b), and evidence of natural background changes in forage fish abundance (Anderson and Piatt 1999), a significant effort was made to document forage fish distribution, abundance, and variability in PWS and Cook Inlet in the 1990's (Thedinga et al. 2000, Brown 2002, Ainley et al. 2003, Abookire and Piatt 2005, Speckman et al. 2005, Piatt et al. 2007c). Survey methods for estimating abundance and distribution of forage fish included acoustic surveys coupled with trawl-sampling (Haldorson et al. 1998, Speckman et al. 2005) and Sound-wide aerial surveys for surface-schooling fish (Brown and Moreland 2000). Aerial surveys were also repeated in 2010-2012 under a separately funded herring research and monitoring program.

A less traditional effort to document forage fish populations from predator diets in the South-central Alaska region was undertaken by the U.S. Geological Survey at Middleton Island, a colony near the continental shelf break about 100 km from the Hinchinbrook Entrance of PWS (Hatch 2013b). This work spanned the time period from 1978 – 2017 (ongoing) and provides an index of forage fish abundance and species composition in seabird diets. The Middleton forage fish index represents the longest continuous time series of a metric related to forage fish in the region. The use of predators as samplers of forage stocks as a complement to more traditional sampling methods that employ boats, nets and acoustics is widely employed around the globe (Sinclair and Zeppelin 2002, Boldt 2005, Yang et al. 2005, Piatt et al. 2007a), and the ability of Middleton Island's long term dataset to demonstrate change in forage stocks is increasingly evident (Thayer et al. 2008, Hatch 2013b).

Since 2012, the forage fish component of the Gulf Watch Alaska program has been working to 1) identify robust methods for monitoring forage fish in PWS, 2) design a repeatable sampling strategy to measure forage fish distribution and abundance over time, and 3) relate forage fish distribution and abundance to habitat. Here we will detail methods and summarize relevant findings from previous and current efforts to document forage fish in the Sound and surrounding areas in south-central Alaska. We will also provide the scientific rationale for a survey design that combines technologies to maximize repeatability and minimize variance in forage fish estimates in the future.

Methods for Sampling Forage Fish in PWS

Historical methods for sampling forage fish in this region include coupled acoustic-trawl surveys, aerial surveys, and sampling predator diets. Each method has advantages and limitations, which will be discussed below. We also discuss the aerial-acoustic design used in 2014 - 2016.

Acoustic-trawl Surveys

Acoustic detection and measurement of fish school signal strength is a common way to estimate fish biomass in the water column. Using this method, calibrated scientific echosounders emit a sound wave into the water at one or more frequencies, and integration of the returned echo signal strength can be translated into fish density and biomass when the species composition, size, and sound-scattering properties (or 'target strength') of the ensonified fish are known. The field of fisheries acoustics has evolved dramatically in recent decades with more focused research on the back-scattering properties of fish, as well as advances in sonar and data processing technology. Still, back-scattering properties of fish and other organisms are variable under different biological and physical conditions, which makes it impossible to reliably identify individual species using returning target signals alone (Horne 2000). We still need expert knowledge of habitat and behavioral differences among species, as well as direct sampling with trawls (or other means of capture/identification) used in conjunction with multi-frequency echosounders in order to classify aggregations and estimate prey biomass.

Acoustic-trawl surveys are used to aid in stock assessments and management of major commercial fisheries including the Peruvian anchovy (Simmonds et al. 2009), Atlantic herring (Overholtz et al. 2006), and Alaskan walleye pollock (Ianelli 2005). While the method is globally established, acoustic estimation of fish biomass is hindered in shallow nearshore waters where most forage fish in PWS aggregate during summer. Acoustic detection of fish schools is limited near the water's surface and in nearshore waters because: 1) technical problems (transducer ringdown and near field range signal noise) usually require that we exclude detections closer than ~2 - 5 m at the frequencies typically employed (120 and 38 kHz, Simmonds and MacLennan 2005), 2) the cone-shaped beam pattern covers a narrower swath at shallower depths, 3) it is dangerous for all but the smallest vessels to survey in nearshore shallow waters (< 5-10 m bottom depth), and, 4) many fishes actively avoid boats under way. Furthermore, acoustic-trawl surveys can be logistically prohibitive due to the high cost of equipment, software, expertise required to collect and analyze the data, and the need for a vessel large enough to accommodate a trawl-based fishing effort (a direct conflict with shallow-water based work nearshore).

Aerial Surveys

Aerial survey methods for estimating population size have been developed for many wildlife taxa including ungulates, marine mammals, and water fowl (e.g., Gasaway et al. 1986, Bodkin and Udevitz 1989, Quang and Lanctot 1991, Laake et al. 1997). Aerial surveys offer the advantage of surveying large areas quickly and at relatively low cost compared to ship-based surveys, but the method has obvious visibility limitations for assessing abundance of fish underwater. In an attempt to develop cost-effective survey methods for nearshore forage fish in PWS, Brown and others (e.g., Brown and Borstad 1998, Brown and Moreland 2000) initiated aerial surveys to document forage fish during the Alaska Predator Experiment (APEX) and Sound Ecosystem Assessment (SEA) projects in the late 1990's. These surveys were conducted from a fixed wing aircraft flying along the shoreline at altitudes of 275-365 m and speeds of 200 km/h. A sighting tube was used to estimate school size, and visual cues (distance from shore, school shape, color, etc.) were used to assign species to observations. On-the-ground validations of aerial observations in 1995-1997 occurred throughout the study period using nets, divers, or cameras. Of 6756 schools, 419 (6.2 %) were validated for species and size distribution. Aerial species misclassification rates were estimated at 6.8 and 20.2% for herring and sand lance, respectively (see Appendix VI in Norcross et al. 1999).

Aerial surveys proved useful for documenting near-surface fish schools in nearshore areas where forage schools tend to aggregate in PWS during summer months (Brown and Moreland 2000). In contrast to vessel surveys, aerial surveys cover large areas quickly, but the precision and accuracy of aerial surveys are affected by variability in sighting conditions, water clarity, vertical distribution of fish in the water column, and observer bias (Norcross et al. 1999, Appendix VI). Furthermore, the combination of traveling at high speeds along a convoluted shoreline under rapidly changing viewing conditions makes density estimation from either strip or line transect surveys difficult. The assumption of complete detection within a narrow strip is hampered by the pilot's ability to stay on course a set distance from shore and the observer's ability to count and identify schools accurately. Line transect survey methods can remedy the issue of incomplete detection, but the detection function from line transects oriented parallel to shore is confounded by the school density gradient relative to the shoreline. In summary, PWS is well suited for aerial surveys of nearshore fish aggregations, but we are still left with uncertainties about species, age class, and density estimates, which can only be addressed by other means.

Predator Diets

Predator diets can provide quantitative information on abundance, distribution, temporal variability, condition and community structure of local prey stocks (Hatch and Sanger 1992, Davoren and Montevecchi 2003, Litzow et al. 2004). Information on the diets of piscivorous seabirds, marine mammals, and predatory fish has been collected at breeding sites in the Gulf of Alaska and elsewhere (Piatt and Anderson 1996, Sinclair and Zeppelin 2002, Yang et al. 2005, Thayer et al. 2008).

Researchers may use a variety of methods to gather diet information about marine predators such as: collect prey remains in scat or regurgitations, sacrifice the animal to examine stomach contents, or in the case of some seabirds, collect whole fish intended for chicks at the nest. The relative occurrence of species in such samples can be a cost effective index of prey availability. The collection of whole fish from chicks also affords advantages over the others because it is minimally invasive for the predator, and information about prey body condition (length, weight, energetics, etc.) can be gathered from whole fish (in contrast to digested food items from stomachs or regurgitations). Drawbacks of using predators as indicators of forage fish stocks are the potential for prey selectivity among generalist vs. specialist predators, non-random sampling of foraging areas, and restrictions on the depth of sampled prey because of predator limitations (Hunt et al. 1991). For example, tufted puffins (*Fratercula cirrhata*) bring a greater diversity of prey items to their nest than the horned puffins (*F. corniculata*) (Hatch and Sanger 1992), suggesting the tufted puffin diets represent a more opportunistic sample of food availability than horned puffins. Some species, like surface-feeding kittiwakes, are limited in their diving depth and their diets are representative only of prey which make it to the surface at some point in their diurnal cycle of vertical migration (Hatch 2013b). Nonetheless, the advantages of easy access and sampling can outweigh the known sampling biases or disadvantages, and in the absence of traditional fisheries surveys for forage fish in the region, the information gleaned from predator diets at seabird colonies provides the best continuous long-term information available on some forage fish species in the northern Gulf of Alaska.

Overview of Gulf Watch Alaska Forage Fish Methods

During 2012-2013 field seasons we conducted fish, seabird, zooplankton, oceanography and nutrients sampling at 27 fixed stations using a stratified systematic design (Arimitsu and Piatt 2014). Acoustics and midwater trawl composition at systematically-placed stations throughout PWS suggested our encounter rate with target species was not sufficient to assess abundance. Frequency of occurrence in trawls (FO) was low for capelin (3.7%), eulachon (3.7%), and euphausiids (11.1%), and catches were overwhelmingly dominated by non-target species (young of the year walleye pollock, FO = 100%, and jelly fish FO = 81.5%). Likewise, beach seines targeting Pacific sand lance had low and variable catches (mean CPUE ± SD = 3.5 ± 10.5 fish per set). Thus we explored ways to improve our ability to sample target fish species.

In 2013 we explored the use of adaptive cluster sampling for at-sea surveys, and tested whether we could use aerial surveys to locate nearshore schools of fish, and then use acoustic/trawl surveys to validate our aerial observations and collect specimens for other purposes as well. Our goal of combing aerial and ship-based methods (hereafter called “aerial-acoustic surveys”) was to markedly increase our encounter rate with target species and increase our acoustic/trawl sampling rates of target species at sea.

Results of aerial-acoustic survey trials in 2013 were mixed. Adaptive cluster sampling (i.e., intensive sampling around schools we found during surveys or by chance) generally involved a high degree of effort and did not facilitate a quantitative means of assessing abundance and distribution at the sound-wide scale. We also devoted three days of ship time to validation of aerial surveys. An experienced spotting pilot directed the ship or a skiff to forage fish schools visible from the plane. Schools were captured with nets, jigs, video, and acoustics whenever possible. The ground crew recorded, and relayed to the pilot, information about fish species, fish size, and depth of the schools. After the pilot left, we conducted acoustic surveys of the area, and we used midwater trawls, gill nets, cast nets, dip nets, jigs, or video to confirm the species composition and fish size for conversion of acoustic backscatter to biomass. In 2014 we developed a new survey design that combined aerial and acoustic survey methods again, but with refinements of sampling strategy (see below).

Combining Technologies: Aerial-Acoustic Survey Design

As a result of the disparity between separate aerial and acoustic survey efforts in PWS, Brown and Moreland (2000) described a need to combine the two survey methods because neither method adequately sampled forage fish schools alone.

Historical aerial survey methods established during the APEX and SEA projects in the late 1990's (Brown and Borstad 1998, Brown and Moreland 2000) serve as the statistical basis for the new survey design that was tested in 2014 and will continue in summer 2015. Shoreline aerial survey data from July 2010 – 2012 (Evelyn Brown, Flying Fish Ltd., Cordova, unpublished data) were analyzed to identify low, medium and high school density regions within the Sound (Figure 2-11). A 5' latitude by 5' longitude grid was overlaid on previous aerial track lines and observations in GIS. An index of school density was calculated for each grid cell such that the total number of schools observed was standardized by effort (length of aerial survey flown in km) and weighted by persistence (number of years schools were observed). Grid cells from high, medium and low density strata were randomly selected for sampling. The optimum sample size in each stratum was chosen to minimize variance of the population mean (Cochran 1977). Near-surface schools in each sampling block were censused by an experienced spotter pilot, and species composition and size of schools were assessed by a fisheries team working from a vessel. Vertical distribution of biomass by species was measured using acoustic transects in a random subset (n = 15) of navigable blocks in the high-density stratum. The acoustic surveys aimed to estimate the proportion of forage fish biomass below the surface that the aerial surveys are unable to sample. Where aerial and acoustic surveys overlap, an index of forage fish availability (aerial school density and acoustically determined biomass) will be compared among regions. The newly redesigned aerial-acoustic survey design aims to increase repeatability compared to the previous design, simplify the data collection and processing effort, and increase certainty in the species composition and school density index derived from aerial observations.

Predator Diets

Although we did not collect predator diets ourselves, we note that diets of several species of seabirds (including kittiwake, tufted puffin, and rhinoceros auklet (*Cerorhinca monocerata*) were monitored on Middleton during the course of our studies (2012-2014), and time series for diets of some species extend back to the 1980s (Hatch 2013; S. Hatch, Institute for Seabird Research and Conservation, Anchorage, unpubl. data). A similar approach in sampling predator diets to monitor prey within PWS has been used in the past for tufted puffins (Piatt et al. 1998), kittiwakes (e.g., Jodice et al. 2009) and pigeon guillemots (e.g., Oakley and Kuletz 1996, Golet et al. 2000). Depending on the status of these species in PWS today (e.g., puffins appear to have declined owing to predation by mink), we believe that systematic sampling of avian forage fish predators has high potential for complementing aerial-acoustic monitoring of forage species in PWS and the Gulf of Alaska.

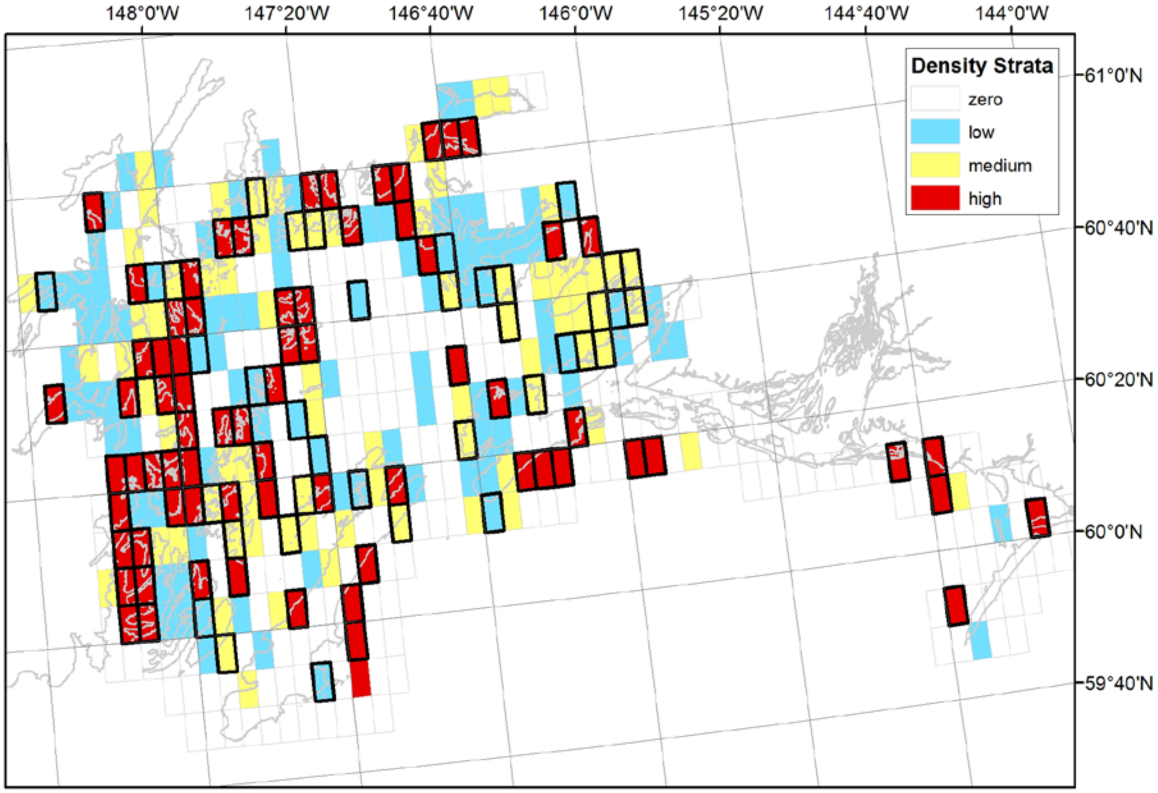

FIGURE -11. DENSITY STRATA SHOWING THE DISTRIBUTION OF FORAGE FISH SCHOOLS (NUMBER OF SCHOOLS/KM FLOWN WEIGHTED BY PERSISTENCE OVER TIME) DURING JULY SHORELINE AERIAL SURVEY COUNTS FROM 2010-2012 (E. BROWN, FLYING FISH LTD., CORDOVA, UNPUBLISHED DATA). FORAGE FISH AERIAL SURVEY SAMPLING BLOCKS (OUTLINED IN BOLD) WERE SELECTED TO BE SAMPLED IN THE GULF WATCH ALASKA PROGRAM'S FORAGE FISH MONITORING COMPONENT BASED ON VARIABILITY WITHIN LOW, MEDIUM, AND HIGH DENSITY STRATA.

Forage Fish Distribution and Abundance in PWS

Several studies have described forage fish distribution and availability in south-central Alaska marine waters in the recent past. Here we summarize species-specific results from these studies.

Capelin

Capelin are distributed in the Sound in the outer bays and exposed beaches in the southwest, north, Montague and Hinchinbrook Island during late spring and summer (Figure 2-12, this study, Brown et al. 2002, Brown 2002). Capelin are also associated with near surface euphausiids in cool turbid waters near tidewater glaciers in PWS and elsewhere (Arimitsu et al. 2008, Arimitsu and Piatt, in prep). Spawning was reported to occur on exposed beaches of Montague and Erlington Islands, and the head of Day Harbor (Brown et al. 2002) and at Port Etches (USGS, unpublished data). Large, irregularly–shaped schools of adult capelin were observed during June-August aerial surveys (Brown 2002). Larval capelin abundance peaks in July, which suggests major spawning events occur in June. Unlike other areas of

Alaska (e.g., Kodiak and Glacier Bay, Pahlke 1985, Arimitsu et al. 2008) prolonged spawning does not appear to occur in PWS (Brown 2002). Although capelin were only occasionally encountered during the APEX work in PWS (Haldorson et al. 1998, Thedinga et al. 2000), in lower Cook Inlet, Capelin occurred more frequently in trawl catches and they increased in abundance between 1996 and 1999 (Abookire and Piatt 2005). Capelin in Middleton Island kittiwake diets showed marked increases during recent cool years from 2000-2003, and 2008-2011 (Figure 2-13, Hatch 2013, Ormseth 2014).

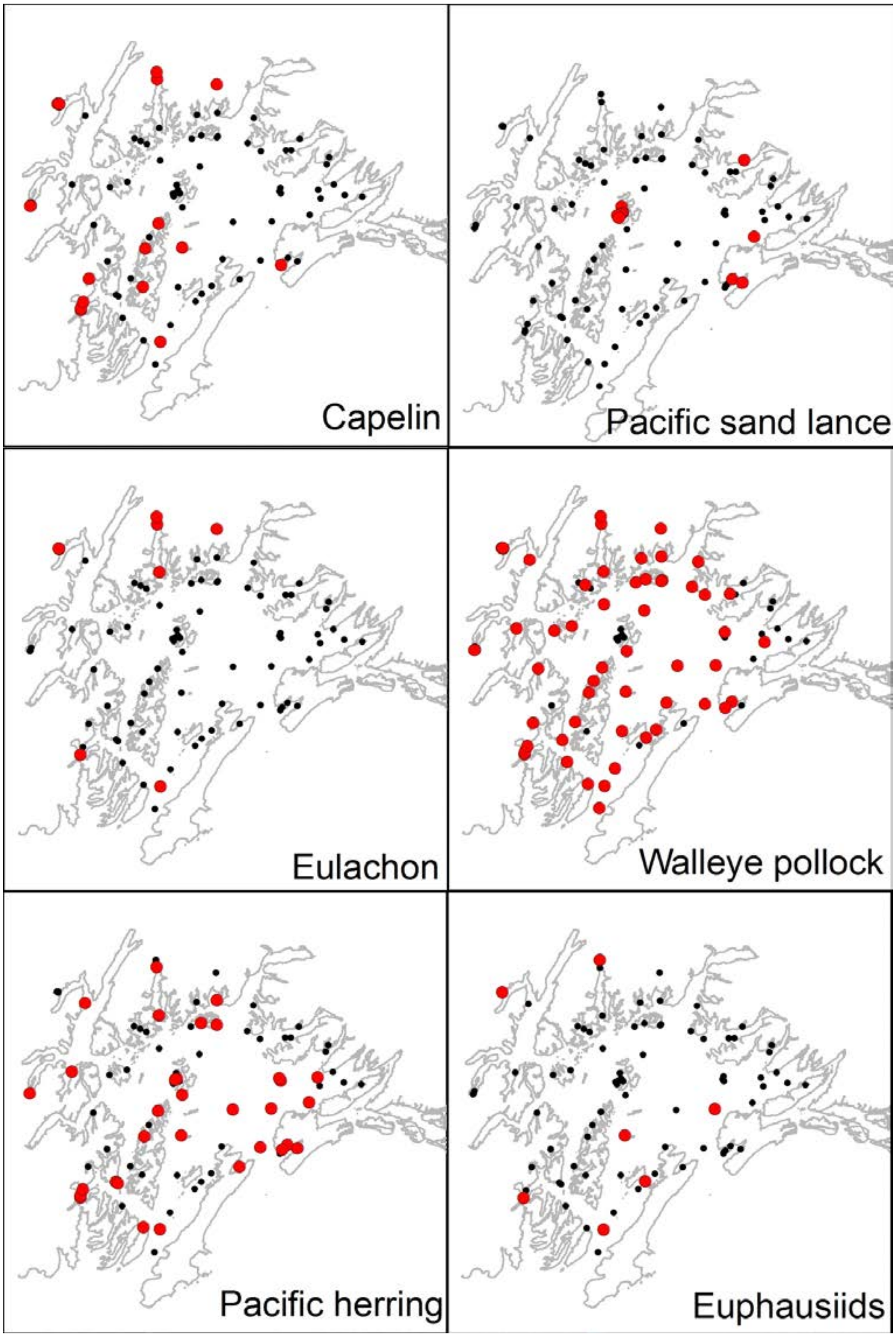

FIGURE -12. DISTRIBUTION OF FISHING EFFORT (INCLUDING MIDWATER TRAWL, BEACH SEINE, JIG, PURSE SEINE AND CAMERA; BLACK CIRCLES) AND LOCATIONS WHERE FORAGE FISH WERE OBSERVED (RED CIRCLES) DURING GULF WATCH ALASKA PROJECT IN SUMMERS OF 2012-2014.

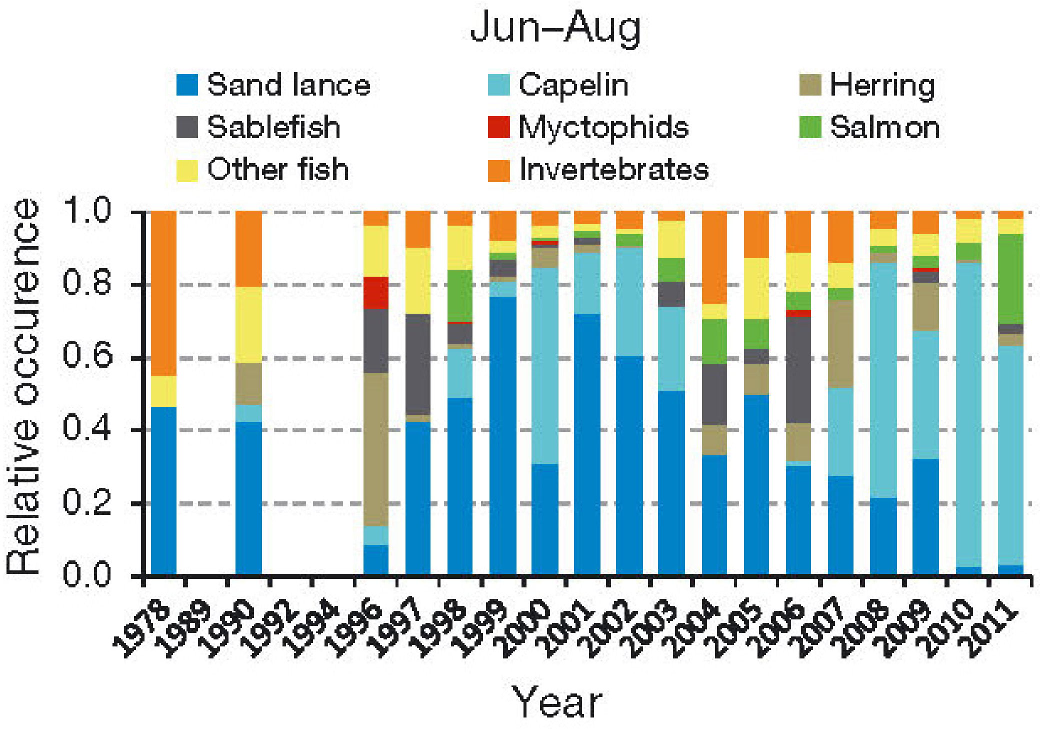

FIGURE -13. BLACK-LEGGED KITTIWAKE DIET COMPOSITION OVER TIME AT MIDDLETON ISLAND, FIGURE FROM HATCH (2013).

Pacific sand lance

Pacific sand lance are associated with shallow depths and sandy substrates (Robards et al. 1999, Ostrand et al. 2005). They spawn on intertidal substrates well after water temperatures cool again from late September to December primarily at age 1 – 3 (Robards 1999). They may be found burrowed in the sand or swimming in schools within the water column. Pacific sand lance abundance in aerial surveys peaked in 1997 and remained high through 1999 (Brown and Moreland 2000). Although Pacific sand lance made up just 0.5% of the acoustic biomass estimates from the APEX years, relative abundance was greatest in the northern region of PWS during 1999 (Thedinga et al. 2000). In 2012-14 we observed aggregations of Pacific sand lance near Naked Island and over Middle Ground Shoal (Figure 2). In lower Cook Inlet, Pacific sand lance were the most abundant forage fish in trawl catches and their numbers increased between 1996 – 1999 (Abookire and Piatt 2005). Near Middleton Island, greater occurrence of Pacific sand lance in diets occurred in 2004, 2006 and 2009, and Pacific sand lance and capelin percent composition in kittiwake diets were negatively correlated over time (Figure 3, Hatch 2013).

Juvenile Walleye Pollock

In summer juvenile walleye pollock are densely aggregated within bays (Stokesbury et al. 2000) and associated with jellyfish in small numbers throughout the upper water column and dispersed throughout the Sound (Purcell et al. 2000). Age-0 walleye pollock dominated midwater trawl catches throughout the Sound in 2012-14 (Figure 2), and the large aggregations of young of the year fish were encountered in Herring Bay and near Glacier Island. Large aggregations of age 1-2 pollock co-occurred with age-2+

herring near Knowles Head and Glacier Island during acoustic surveys in 2013. Adult pollock aggregate near the bottom in deep waters throughout the Sound, and they are caught in trawls with capelin and euphausiids near tidewater glaciers.

Eulachon

Eulachon spawn in the Copper River Delta during spring, and they occur in marine waters near the outer passes in the southwest Sound, and off the southern tip of Montague Island (Brown et al. 2002). Catch per unit effort from small-mesh trawl surveys in the Gulf of Alaska was below the long term average in 2011-12 (Zador 2013). We observed juvenile and adult eulachon associated with near-surface aggregations of euphausiids and other dispersed forage fish near tidewater glaciers (Figure 2-12).

Pacific herring

Pacific herring are the focus of a much larger study, which this project is also in close collaboration with, to investigate the reason for the lack of recovery since the early 1990's. Thus the species is discussed in greater detail elsewhere. Along with walleye pollock, Pacific herring were the most frequently encountered species during work in summers of 2012 – 2014 (Figure 2-12). They were also a regular part of seabird diets at Middleton Island, especially during the latter half of the 2000s (Hatch 2013b).

Euphausiids

In the Gulf of Alaska species specific changes in abundance of euphausiids occurred between 1998 and 2003. *Thysanoessa inermis* increased in abundance from 1998 to 2002, and declined in 2003, and *Euphausia pacifica* declined between 1998 and 2001 then increased from 2001 to 2003 (Pinchuk et al. 2008, Wilson et al. 2009). We encountered five species of euphausiids in PWS, including *E. pacifica, Thysanoessa spinifera, T. inermis, T. rashi,* and *T. longipes.* The presence of spermatophores in *T. spinifera* indicated spawning in July within glacial fjords.

Summary/Recommendations

In this synthesis we summarized several coordinated efforts to document the distribution and abundance of forage fish in PWS and surrounding areas over the past two decades. Due to differing life histories of multiple species with clustered distributions and highly variable populations, forage fish are difficult to study. Sampling methods include acoustic-trawl surveys, aerial surveys of near-surface schooling fish, and the use of predator diets as indicators of forage fish abundance over time. A monitoring program that includes a variety of methods will improve our ability to document change over time. In PWS we are testing an improved forage fish survey design that combines aerial and acoustic surveys. Due to the relative ease and efficiency that a predator diet component can provide (see Hatch 2013), addition of predator diet studies could further strengthen this aspect of the Gulf Watch monitoring program. Continued monitoring will be critical to understanding the role of natural and anthropogenic factors on forage fish populations in the region, and provide important information about the role forage fish play in the ecosystem.

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